Project deliverables

Deliverable #D3.1

Preliminary analysis of indicators and methodologies for decision-making

Funded by

Financial support has been provided by PRIMA; a program supported by the European Union

AGREEMAR

Adaptive agreements on benefits sharing for managed aquifer recharge in the Mediterranean region

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Preliminary analysis of indicators and methodologies for decision-making

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Executive summary

Deliverable D3.1 provides a preliminary analysis of indicators and methodologies for decision-making. It highlights the importance of integrated water management and the use of indicators in Managed Aquifer Recharge (MAR) projects. The report highlights the significance of addressing hydric stress in the Mediterranean region and explores the concept of comprehensive recharge and recovery. It also promotes the consideration of alternative conjunctive use of surface water and groundwater resources to reduce expenses. The findings underscore the value of environmental, socio-economic, and governance indicators in assessing the sustainability and effectiveness of water management practices in MAR projects.

Work package	Work package 3. Adaptive governance framework
Deliverable number & title	D3.1. Preliminary analysis of indicators and methodologies for decision-making
Partner responsible	Universitat Politècnica de València (UPV)
Deliverable author(s)	Syrine Ghannem (UPV), Rafael J. Bergillos (UPV), Joaquín Andreu (UPV), Javier Paredes-Arquiola (UPV), Abel Solera (UPV)
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Planned delivery date	31.07.2023
Actual delivery date	31.07.2023
Citation	Ghannem, S., Bergillos, R.J., Andreu, J., Paredes-Arquiola, J., Solera, A. 2023. AGREEMAR Deliverable D3.1: Preliminary analysis of indicators and methodologies for decision-making. Available online at https://www.agreemar.inowas.com/deliverables.
Dissemination level	PU (Public)

Revision history

Version	Date	Author	Remarks
V0.1	02.06.2023	Syrine Ghannem (UPV)	First version
V0.2	16.06.2023	Rafael J. Bergillos (UPV)	Second version
V0.3	23.06.2023	Javier Paredes-Arquiola (UPV)	Third version
V0.4	30.06.2023	Abel Solera (UPV)	Fourth version
V0.5	04.07.2023	Joaquín Andreu (UPV)	Fifth version
V0.6	05.07.2023	Rafael J. Bergillos (UPV)	Sixth version
V1.0	26.07.2023	Syrine Ghannem (UPV)	Feedback from project partners included

Abstract

This report presents a preliminary analysis of indicators and methodologies for decision making in Managed Aquifer Recharge (MAR) projects, with a focus on enhancing water management practices in the Mediterranean region. Emphasizing the importance of integrated water management, the report highlights the pivotal role of indicators in driving successful MAR initiatives.

By adopting a comprehensive approach to recharge and recovery, MAR projects demonstrate their potential to effectively combat water scarcity and ensure the sustainable use of water resources. An essential consideration is the integration of surface water and groundwater resources, optimizing water availability while reducing operational expenses and enhancing overall sustainability.

The report underscores the significance of environmental, socio-economic, and governance indicators as critical tools for assessing the effectiveness and long-term sustainability of water management practices within MAR projects. By providing valuable insights to decision-makers, these indicators enable informed choices in resource management.

Legal aspects of MAR are also addressed, including an examination of the existing legal framework in European water policy and its application in specific Mediterranean countries. In-depth case studies on MAR applications offer valuable insights into the challenges faced and lessons learned from various projects.

Overall, the report highlights the crucial role of indicators and methodologies in effective decision-making for MAR projects. It advocates for the adoption of integrated water management practices and the utilization of indicators to ensure sustainable water resource utilization in the Mediterranean region.

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1. Introduction

1.1 Background and importance of the project in terms of improving decision-making

Water scarcity is a major challenge for Mediterranean countries, which are characterized by arid and semi-arid climates, heavy dependence on agriculture and tourism, and high socioeconomic value of water resources. In this region, water resources are unevenly distributed in space and time due to high spatial and temporal variability of precipitation and derived hydrological variables as, for instance, flows in rivers. Factors such as agricultural intensification, population growth, and seasonal coastal tourism contribute to high water stress in the basins. As a consequence, overexploitation of aquifers, particularly in the northern Mediterranean countries, has led to depletion of water tables and, in cases of coastal aquifers, to seawater intrusion, resulting in drinking water shortages and agricultural land degradation. These problems are exacerbated by the effects of climate change.

The AGREEMAR project holds great significance in improving decision-making regarding water resources management in the Mediterranean region. By developing an adaptive governance framework and management tools, it aims to provide valuable support to water policy makers and managers in achieving Sustainable Integrated Water Resources Management (IWRM). This will be reached by means of managed aquifer recharge (MAR), referring to the intentional recharge and optimized storage of water to aquifers for subsequent use or environmental benefit.

1.2 Purpose and objectives of the deliverable

The conjunctive use of surface water and groundwater presents a promising paradigm within the realm of water management. By acknowledging their hydraulic connection and promoting their integrated utilization, it becomes possible to address challenges related to water supply and water quality. This approach extends beyond arid regions, encompassing areas facing diverse water-related issues. However, to fully harness the benefits of conjunctive use, it is imperative for planners and decision-makers to enhance their understanding and appreciation of aquifers as crucial components of the water resources systems. This recognition unlocks the potential of groundwater as an abundant and cost-effective resource, further contributing to sustainable water management practices.

The primary objective of this deliverable is to conduct a comprehensive analysis of indicators and methodologies that can effectively inform decision-making processes. The focus is on developing a systematic approach to calculate indicators specifically tailored to assess the potential impact of MAR on river basin scale dynamics. Recognizing the interconnected nature of groundwater and surface water resources, it is imperative to adopt a holistic perspective and manage these resources as an integrated system.

While a detailed aquifer model provides valuable insights into the behavior and characteristics of the groundwater system, it alone is insufficient to capture the broader implications of MAR. To gain a comprehensive understanding of the influence of MAR on the entire basin, as well as on its feasibility, decision support systems must be employed. These systems help assess the complex interactions and feedback mechanisms between groundwater and surface water resources, enabling stakeholders to make informed decisions.

Furthermore, the integration of surface water and groundwater management requires the identification and use of appropriate indicators that can effectively measure changes in water quantity, water quality, and ecological health. By quantifying these indicators and assessing their variations before and after MAR-related activities, decision-makers can evaluate the effectiveness and sustainability of such interventions.

Additionally, this deliverable emphasizes the need for a collaborative and participatory approach to water resources management. Effective governance frameworks that facilitate stakeholder engagement, transparency, and accountability are crucial for ensuring the long-term success of MAR projects. By involving various stakeholders, such as water authorities, local communities, and user groups, a comprehensive understanding of the social, economic, and environmental dimensions can be achieved.

In conclusion, this deliverable highlights the importance of adopting a holistic approach in managing water resources, considering both surface water and groundwater as interconnected components. It underscores the significance of utilizing suitable indicators and decision support systems to assess the impacts of MAR at the river basin scale. By integrating these approaches and promoting collaborative governance, sustainable and informed decisions can be made to ensure the effective management of water resources.

1.3 Importance of indicators and methodologies in decision-making for water management

Indicators and methodologies provide a systematic and objective approach to assess the current state and trends of groundwater resources, enabling evidence-based decision-making. By utilizing well-defined indicators, decision makers can quantify and track important parameters such as piezometric level, water quality, recharge rates, and abstraction rates. These indicators provide valuable insights into health and sustainability of aquifer systems, allowing for informed decision-making regarding the allocation and management of groundwater resources.

Indicators help in monitoring key parameters and are essential for evaluating the effectiveness and performance of different management strategies, interventions, and policies. They play a crucial role in identifying potential risks, vulnerabilities, and impacts associated with groundwater management decisions, enabling proactive measures for mitigation. Robust indicators enable decision makers to assess the outcomes of various management approaches, facilitating adaptive management and the ability to adjust strategies as necessary to ensure sustainable groundwater use.

Well-defined methodologies provide frameworks for data collection, analysis, and modeling, ensuring consistency, comparability, and reliability of information used in decision-making processes. These methodologies guide the systematic collection of data, standardize analytical procedures, and establish modeling techniques to understand the complex dynamics of groundwater systems. By employing rigorous methodologies, decision makers can rely on accurate and trustworthy information to evaluate the potential outcomes and impacts of different management decisions.

2. Overview of integrated water management and water governance

2.1 Integrated Water Resources Management: a comprehensive framework for sustainable utilization of water resources

In the latter decades of the twentieth century, there was a growing recognition of the urgent need to prioritize the sustainable utilization of water resources to avert a potential global water crisis. This concern was prominently addressed during the United Nations Conference on Water held in Mar del Plata (Argentina) in 1977, where comprehensive discussions took place regarding various aspects of integrated water management, which emphasized the importance of adopting holistic strategies to ensure the long-term viability and equitable utilization of water resources on a global scale (Ngene et al., 2021).

The Integrated Water Resources Management (IWRM) approach promotes the harmonized development and governance of water, land, and associated resources to optimize economic and social well-being in an equitable manner while ensuring the sustainability of crucial ecosystems. It entails enhanced coordination in the development and management of various components, including land and water resources, surface water and groundwater, river basins and their coastal and marine environments, and the interests of both upstream and downstream stakeholders (GWP, 2004). It emphasizes the integration of different objectives, striving for optimal solutions and trade-offs when necessary. Additionally, IWRM emphasizes the significance of temporal scales, encompassing the natural fluctuations in water availability over seasons, years, and even long-term periods. Furthermore, it highlights the need to anticipate and evaluate the implications of present actions on future generations, thus fostering sustainable water management practices (Savenjie and Van der Zaag, 2008; Nagata et al., 2022).

IWRM functions as a strategic framework aimed at mitigating the challenges posed by fragmentation in water governance systems. This fragmentation manifests in diverse ways, such as functional, societal, and institutional fragmentation. By adopting an integrated approach, IWRM seeks to address these fragmentation issues and foster cohesive and coordinated water management practices (Lubell et al., 2013).

The fundamental objective of IWRM is to facilitate collaboration, joint accountability, and integration within these fragmented governance systems (Edelenbos and Teisman, 2011). By promoting cohesive efforts, IWRM aims to enhance the effectiveness and efficiency of water management practices, ensuring a more holistic and sustainable approach to water resources governance.

2.2 Water governance: pillars and concept

Water governance encompasses a diverse array of elements arising from the intricate nature of water as a vital resource, its multifaceted uses, and the implications for societal organization. The objectives pursued by water governance and their adaptation to evolving material conditions in societies significantly shape the discourse and practices within the field. It is important to recognize that the context in which societies interact with water influences how their relationship is characterized, ultimately determining the rules and procedures that underpin water governance and often giving rise to divergent perspectives (Srinivasan, Lambin, Gorelick, Thompson, & Rozelle, 2012).

When it comes to water governance, several key questions are subject to ongoing debates. Firstly, the issue of participation arises, focusing on the inclusion of stakeholders in decision-making processes. Who should have a voice in shaping water-related policies and practices? Secondly, the geographical and political scales at which governance institutions operate are deliberated. What is the most effective level of governance for the management of water resources? Lastly, the role of market or non-market criteria in water allocation is discussed. Should water allocation be driven primarily by market mechanisms or consider alternative factors?

While it is challenging to consolidate these elements into a singular framework, it is evident that they significantly shape the conceptualization, discourse, and practical implementation of water governance. Water permeates all aspects of human activities, and our interactions with it as a natural resource are embedded within broader narratives concerning the human-nature relationship. The narrative of "scarcity" historically justified infrastructure development as a response and supported the adoption of universal principles, such as market-based approaches and the preservation of natural hydrology, to mediate competing water uses. This review critically examines the implications and limitations of the scarcity narrative within water governance (Swyngedouw, 1999).

The concept of "governance" itself influences discussions within the water sector. Although water governance is often considered a distinct domain, governance principles inevitably shape these discussions. Efforts to control, manage, and govern water usage date back to the early stages of agriculture and human settlement. The development of hierarchical state formations played a vital role in facilitating water management systems, as observed in various societies worldwide. However, the specific arrangements of water governance are influenced by diverse factors such as physical conditions, climate, socio-economic circumstances, power dynamics, and religious beliefs (Woodhouse and Muller, 2017).

Groundwater governance encompasses the framework and guiding principles for collective and responsible actions that ensure the control, protection, and socially sustainable use of groundwater resources for the benefit of humanity and the systems dependent on groundwater. Groundwater management involves the activities carried out by authorized agents to develop, utilize, and sustainably protect groundwater resources. This framework includes laws, regulations, and customary practices related to groundwater use, as well as processes to engage the public sector, private sector, and civil society, and actions to enforce these laws, policies, and decisions. It consists of routine, practical, and effective approaches aimed at achieving specific predetermined goals and objectives (EGASE, 2022).

According to FAO/Global Environment Facility (GEF) Groundwater Governance Project (FAO, 2015), groundwater governance consists of four components:

1. Legal and regulatory framework.
2. Accurate and widely shared knowledge of groundwater systems, including awareness of their existence.
3. Institutional framework characterized by effective leadership, good organization, stakeholder engagement, and functional mechanisms for coordinating groundwater with other sectors.

4. Policies, incentive structures, and plans aligned with societal objectives.

Key elements of groundwater governance include integrated local solutions linked to higher-level approaches, user participation, as well as transparency, information and communication, which are essential for awareness and accountability.

3. Explanation of the role of indicators and methodologies in decision-making

3.1 How do indicators and methodologies shape decision-making in water resources management?

Decision-making in water resources management is of paramount importance as it directly influences the sustainable and effective use of this critical resource. With growing demands, increasing water scarcity, and the need to balance multiple sectors, making informed decisions becomes crucial. Indicators play a significant role in this process by providing valuable insights and facilitating the decision-making process whether at the individual, organizational, or governmental level. They provide valuable information that guides choices and actions (Cornescu and Adam, 2014).

The use of indicators in decision-making allows for a comprehensive understanding of the complex interrelationships within river basins (Cornescu and Adam, 2014; Pires et al., 2017). While local-scale decisions are important, considering the broader scale of a river basin is critical. River basins encompass interconnected water systems, including surface water and groundwater, and are influenced by various stakeholders and activities. By adopting a basin-wide perspective, decision-makers can account for cumulative impacts, optimize water allocation, and address the needs of all users.

To facilitate decision-making in river basins, decision support system (DSS) tools are invaluable. DSS tools integrate data, models, and indicators to provide a holistic view of water resources and support decision-making processes. These models provide a representation of the current condition of the water system, encompassing water resources, demands, and supplies. DSS tools enable the analysis of multiple scenarios, the assessment of trade-offs, and the evaluation of potential outcomes considering water resource suitability, costs, benefits, and environmental impacts. By utilizing DSS tools, decision-makers can consider various indicators and their interdependencies, enhancing the robustness and effectiveness of their decisions (Salewicz & Nakayama, 2004; Zeng et al., 2021; Pardo-Loaiza et al., 2021; 2022a; 2022b; Monico et al., 2022).

DSS tools, indicators and related methodologies contribute to stakeholder engagement and participatory decision-making processes (Andreu et al, 2009). By presenting relevant data and visualizations, these tools facilitate dialogue, foster collaboration, and promote shared understanding among stakeholders. This inclusive approach enables the incorporation of diverse perspectives, local knowledge, and societal values in decision-making processes, ultimately leading to more sustainable and equitable outcomes.

3.2 Can indicators drive effective decision-making for managed aquifer recharge?

Indicators serve as measurable parameters that reflect the status, trends, and changes in water resources. They provide a standardized and objective basis for assessing the impact of MAR on various aspects, such as water quantity, water quality, and ecological health. By establishing baseline indicators and monitoring their variations over time, decision-makers can gauge the success of recharge activities, identify potential issues, and make informed adjustments to optimize outcomes (Escalante et al., 2019).

Methodologies, on the other hand, provide systematic approaches and analytical frameworks for analyzing complex data and evaluating different scenarios. They enable stakeholders to assess the potential effects of MAR on water availability, water quality, and overall water resources management within a river basin context. By employing robust methodologies, decision-makers can conduct rigorous assessments, compare alternative strategies, and identify the most effective and sustainable options for MAR implementation.

Moreover, indicators and methodologies support the integration of MAR within the broader water resources management framework. They facilitate the consideration of multiple factors, such as climate change impacts, competing water demands, and ecological considerations. Through their application, decision-makers can evaluate trade-offs, prioritize actions, and align MAR initiatives with the overarching goals of sustainable water management. They also contribute to transparency, accountability, and stakeholder engagement. By using standardized and transparent indicators, decision-making processes become more inclusive and accessible to all relevant parties. Additionally, methodologies provide a common language and analytical framework that enable effective communication and collaboration among stakeholders, fostering a shared understanding of the challenges and opportunities associated with MAR.

In summary, indicators and methodologies provide the necessary quantitative information and analytical tools to assess the impact, optimize outcomes, and promote sustainable practices. By leveraging these tools effectively, decision makers can ensure the successful implementation of MAR projects while safeguarding water resources and supporting the long-term resilience of river basins.

3.3 What challenges arise in decision-making based on indicators?

Indicators serve as powerful tools for decision-making, allowing to assess, analyze, and forecast various aspects of interest. However, it is important to acknowledge that the power of indicators can also be their weakness. When attempting to capture a broader and complex topic, such as sustainable development or water resources management, selecting representative indicators becomes a challenging task. The selection process requires careful consideration to ensure that the chosen indicators truly reflect the essence of the topic and provide meaningful information. Failure to do so may result in a loss of important details or even manipulation of data, which can lead to misguided decision-making (Cornescu and Adam, 2014).

The challenge lies in finding indicators that can effectively capture the multidimensional nature of the topic at hand. For instance, in the context of water resources management, it is essential to consider factors such as quantity, quality, accessibility, and sustainability. Choosing indicators that can accurately reflect these aspects is crucial for developing a comprehensive understanding of the water resources system (Spangenberg, 2004; Pires et al., 2017).

To mitigate the risk of information loss or manipulation, a robust methodology is needed for indicator selection and analysis. Transparency, robust data collection processes, and rigorous analytical techniques are essential in ensuring the reliability and credibility of the indicators used. Stakeholder engagement and expert input are also valuable in validating the relevance and accuracy of the chosen indicators.

4. Ensuring sustainable managed aquifer recharge: safeguarding water resources integrity

4.1 Importance of conjunctive use of water resources

Within the broader perspective of addressing global water challenges, the conjunctive use of surface water and groundwater emerges as a holistic approach that emphasizes the integration of these two essential water sources. It recognizes their interconnectedness and accounts for the potential changes in flow, levels, and water quality that can occur in rivers and aquifers due to the utilization of either resource. The conjunctive use approach is not limited to arid or water-scarce regions but finds relevance in areas facing water supply and water quality issues.

Despite the rational recognition of aquifers as integral components of the water resources system, the full acceptance of this concept by planners and decision-makers remains incomplete. The term "integrated water resources management" has been used to encompass all water sources, including the sea, lakes, rivers, and streams (Cardwell et al., 2006). However, references to groundwater in technical documents, such as those produced by the Global Water Partnership (GWP), often remain limited. This limitation arises primarily from a lack of awareness and a limited understanding among planners regarding the immense potential that groundwater offers. Further exploration of the advantages of integrating groundwater is needed, considering its widespread availability and often cost-effective nature (Sahuquillo et al., 2010).

In complex water systems, the benefits of conjunctive use may not be immediately evident due to the limited number of comprehensive comparisons between different conjunctive use scenarios, even when using simplified models. It is crucial to employ appropriate modeling approaches to conduct thorough and cost-effective assessments of various alternatives. Drawing from experiences in countries like Spain, as well as other regions, over the past two decades, incorporating groundwater into water management can provide significant advantages. Particularly in cases where aquifers hold substantial resources or have extensive coverage, the inclusion of groundwater becomes a pivotal and decisive factor. Recent trends have cast doubt on the effectiveness of structural solutions, leading to a greater focus on optimizing existing infrastructures rather than constructing new ones. Therefore, when seeking to improve water availability in a given area, it is essential to carefully consider the potential integration of aquifers into the overall water management system (Sahuquillo et al., 2010).

4.2 Assessing the impacts of managed aquifer recharge

Ensuring the sustainability and integrity of water resources within a river basin requires a careful consideration of the potential impacts of MAR activities. While MAR techniques offer valuable means to replenish depleted aquifers, it is crucial to avoid, or minimize, unintended negative consequences on the wider water resources system. To achieve this, the use of indicators and methodologies for integrated water management and water governance becomes imperative.

By employing appropriate indicators, we can assess the effectiveness and potential risks associated with MAR projects. These indicators can include measurements of groundwater levels, water quality parameters, and the ecological health of rivers and streams. By monitoring these indicators, stakeholders can proactively identify any adverse effects of MAR and act appropriately to mitigate them. Moreover, comprehensive methodologies that integrate surface water and groundwater management are necessary to evaluate the cumulative effects of MAR alongside other water-related interventions within the river basin.

Integrated water management and water governance frameworks provide the necessary tools for effective decision-making and collaboration among various stakeholders involved in MAR projects. These frameworks consider the social, economic, and environmental aspects of water management, ensuring that recharge activities align with broader water resource management goals. By involving multiple actors, such as government agencies, water user associations, and local communities, in the decision-making process, a more inclusive and informed approach can be adopted. This collaborative effort promotes transparency, accountability, and equitable distribution of water resources.

Furthermore, successful MAR implementation requires a comprehensive understanding of the interconnected nature of surface water and groundwater systems within the river basin. It is essential to consider the hydrological dynamics, water availability, and competing water demands to achieve a balanced approach. Integrating water management and governance practices encourages dialogue, coordination, and knowledge sharing among stakeholders, enabling them to collectively address challenges and identify innovative solutions.

In summary, to ensure that MAR activities contribute positively to water resource sustainability, it is crucial to employ indicators and methodologies for integrated water management and water governance. These tools facilitate a comprehensive understanding of the impacts of MAR on the river basin's water system, enable informed decision-making, and promote collaborative actions. By embracing an integrated approach, stakeholders can strike a balance between aquifer recharge and the overall health and resilience of the water resources system, ultimately safeguarding water availability for present and future generations.

4.3 Holistic considerations for sustainable MAR in river basins

Managed aquifer recharge has been used in arid countries to store surface water or surplus volumes that would otherwise go unused (Stefan and Ansems, 2018). In the early decades of the 20th century, it gained prominence in California and other arid regions to harness the flows of ephemeral rivers. In arid regions, the most common method of recharging local surface waters is through spreading basins, trenches, or riverbeds. These basins or trenches retain water for infiltration in areas with highly permeable soils, usually after a prior sedimentation process in other compartments. Subsequently, the scope of MAR expanded to include imported water (Sahuquillo et al., 2010).

Over pumping of groundwater over an extended period poses significant challenges to the sustainability of aquifer systems. Over time, the unsustainable rate of groundwater extraction has outpaced natural recharge, resulting in a continuous decline of groundwater levels. In the quest for sustainable water resource management MAR has emerged as a promising technique to replenish depleted aquifers and enhance water availability. Its technologies focus on enhancing the amount of groundwater available by facilitating the infiltration of water into aquifer formations. Alongside rainwater, treated wastewater, and desalinated seawater, MAR is considered one of the alternative water sources frequently integrated into comprehensive water management strategies. Implementing MAR is one approach to ensure water supply, mitigate certain impacts of climate change, and address overall groundwater quantity and quality issues. However, it should be noted that MAR is not a substitute for sustainable groundwater management, which requires reducing abstraction rates and aligning water withdrawal with resource availability (Casanova et al., 2016).

To ensure the long-term success and effectiveness of MAR projects, it is crucial to acknowledge that these projects should not be implemented in isolation. Instead, they must be carefully planned and executed within the broader context of a river basin, considering the complex interactions and interdependencies within river basins. Holistic considerations encompass various elements, including water availability, water quality, environmental impacts, socio-economic factors, stakeholder engagement and effective governance.

Many past and ongoing MAR initiatives have often focused solely on aquifer replenishment without considering the intricate dynamics of the surrounding river basin. Ignoring the interconnectedness of surface water and groundwater systems, as well as the influence of land use practices, climate patterns, and ecological factors, can lead to unintended negative consequences. These consequences may include reduced water availability, compromised water quality, ecological disturbances, and conflicts among water users.

5. Review of indicators for decision-making in water management

5.1 Indicators used in water management decision-making

Literature suggests that there are a variety of indicators that can be used for integrated water management and governance. These indicators support long-term planning, resilience building, and adaptive management. They provide the necessary tools to anticipate and respond effectively to changing conditions and uncertainties. By regularly monitoring indicators and employing adaptable methodologies, decision-makers can adjust management strategies, optimize resource allocation, and promote the sustainable use of groundwater over the long term (Brugmann, 1997; Ioris et al., 2008).

Developing a relevant indicator requires considering several important features that have been identified in the literature. The indicator should be specific, allowing for clear and precise identification of the desired results. It should also be measurable, preferably in a quantitative manner, enabling the measurement of progress or performance. Practicality is another crucial aspect, as the indicator should be practical and feasible to implement in real-world scenarios. It should be accessible, cost-effective, and applicable in various contexts. Furthermore, the indicator should rely on available data or allow for data collection without excessive effort. This ensures that the necessary information can be obtained consistently and efficiently. Transparency is also key, as the methodology and selection process used for the indicator should be transparent and well-documented, enhancing the credibility and reliability of the results. Finally, the indicator should be grounded in sound scientific principles and evidence, drawing upon established theories, models, or empirical studies to ensure validity and relevance. By incorporating these features, an indicator becomes a powerful tool for monitoring and assessing progress in different domains, providing valuable insights for decision-making and policy formulation (Cornescu and Adam, 2014).

There are several indicators used for integrated water management and governance. The OECD Water Governance Indicator Framework (OECD, 2015) is a voluntary self-assessment tool that can be used to assess the governance of water resources. The framework is composed of 36 water governance indicators and a checklist containing 100+ questions on water governance. The framework assesses the governance of water resources, including the institutional, legal, and economic frameworks that support it.

5.2 Key indicators for sustainable water resources management: Insights from the AGUAMOD project

To ensure integrated water management, the AGUAMOD Project proposed an approach combining a series of river basin water requirements (drinking water, agriculture, industry, environmental flows, etc.), with numerical models simulating water availability and flows in different parts of the basin. A social and economic assessment of water resources and an analysis of the quality of water governance were also carried out. In addition, the consideration of different climate change scenarios, together with the simulations provided by the models, will make it possible to anticipate future water needs from a social and environmental point of view. This approach entailed three environmental indicators considering their relevance for assessing the availability of water resources in terms of agricultural and urban demand, as well as two indicators assessing hydrological alteration. From a socio-economic point of view, 7 indicators were selected to assess water productivity in the primary sectors, especially in agriculture, in the secondary and tertiary sectors, as well as the intensity of water use in the generation of employment in the primary, secondary and tertiary sectors. The 4 indicators related to governance result from the analysis of the hydrological plans of each basin and allow evaluating the degree of transparency in public consultations, the tools, public involvement in dialogue and the degree of participation of the population (AGUAMOD, 2019).

5.2.1 Environmental indicators

Environmental indicators play a crucial role in water resources management, providing valuable insights into the sustainability and health of ecosystems. In the context of the AGUAMOD project, three key environmental indicators have been identified: ENV1: Urban Water Supply Sustainability (SHU), ENV2: Hydrological Alteration indicator (IAH), and ENV3: Agricultural Water Sustainability (SHA).

ENV1, the Urban Water Supply Sustainability indicator (SHU), combines three sub-indicators - reliability, resilience, and vulnerability - to assess the satisfaction of urban water supply demand. Calculated at the scale of each Urban Demand Unit (UDU), which represents aggregated urban areas drawing water from the same source, the indicator provides valuable information at the exploitation system and hydrographic demarcation levels.

ENV2, the Hydrological Alteration indicator (IAH), measures the degree of alteration that resource management practices impose on ecosystems. This indicator utilizes statistical parameters derived from daily streamflow data to evaluate the modification of the current flow regime compared to its natural state. It is calculated at the scale of river segments within each exploitation subsystem, contributing to a comprehensive understanding of hydrological alterations.

ENV3, the Agricultural Water Sustainability indicator (SHA), encompasses three sub-indicators - reliability, resilience, and vulnerability - related to agricultural water demand satisfaction. Similar to ENV1, this indicator is calculated at the scale of each Unit of Agricultural Demand (UDA), representing aggregated irrigated areas that extract water from the same source. The values are then aggregated at the exploitation system and hydrographic demarcation levels, providing insights into the overall sustainability of agricultural water use.

These indicators serve as valuable tools for decision-makers in assessing the ecological impacts and sustainability of water management practices. By quantifying and monitoring key aspects such as water supply reliability, hydrological alteration, and agricultural water sustainability, stakeholders can make informed decisions to ensure the long-term health and balance of water resources. The spatial and temporal scales considered in these indicators allow for a comprehensive understanding of the dynamics within river basins, facilitating effective decision-making and promoting sustainable water management practices.

5.2.2 Socio-economic indicators

Socio-economic indicators play a crucial role in understanding the relationship between water resources and economic activities. The AGUAMOD project incorporates several socio-economic indicators to assess the productivity of water in different sectors. One such indicator is **ECON1**, which measures the average apparent water productivity in the primary sector, including agriculture, livestock, and forestry. This indicator calculates the Gross Value Added (GVA) generated by these economic sectors divided by the virtual water used. It provides insights into the monetary value produced per unit of water volume dedicated to these activities.

Additionally, **ECON2** focuses specifically on the agricultural sector. It evaluates the average apparent water productivity by dividing the economic value of agricultural production by the direct water used, accounting for both irrigation and effective rainfall. This indicator helps understand the economic output generated per unit of water volume used in agriculture.

Moreover, **ECON3** examines the water productivity in the secondary sector, encompassing industrial and construction activities. By dividing the GVA of these sectors by the virtual water used, it offers insights into the economic value produced per unit of water volume in these sectors.

Furthermore, the tertiary sector, also known as the service sector, is analyzed through **ECON4**. This indicator calculates the apparent water productivity by dividing the GVA generated in the sector by the virtual water used, including water dedicated to human consumption. It sheds light on the economic value produced per unit of water volume in the service sector.

In addition to measuring productivity, socio-economic indicators also assess water usage intensity in relation to employment. **ECON5**, **ECON6**, and **ECON7** evaluate the water use intensity per employee in the primary, secondary, and tertiary sectors, respectively. These indicators help assess the pressure on water resources concerning employment and aid in policy-making for water allocation among different economic sectors.

These socio-economic indicators derived from the AGUAMOD project offer valuable insights into the relationship between water usage, economic productivity, and resource allocation across various sectors, contributing to sustainable water management and informed decision-making.

5.2.3 Governance indicators

Governance indicators play a crucial role in assessing the effectiveness of water resource management. Several indicators have been developed to measure different aspects of governance. These indicators, proposed by the AGUAMOD project, provide valuable insights into the governance practices within water management. One such indicator is **GOB1**: Decline of governance tools at the local level, which focuses on the local level. It encompasses three variables: TerrDispo, indicating the existence of participation activities throughout the territory; ReunionTerr, indicating whether territorial meetings have been conducted exclusively; and AppliTerr, which assesses the existence of territorial boundaries within the basin for replicating participation schemes. Another important indicator is **GOB2**: Degree of transparency, which measures the degree of transparency. It combines three variables: DiffAutre, indicating the use of means other than the press to communicate the opening of public consultations; Diffpresse, assessing the dissemination of consultation periods through different media channels; and DispoDoc, evaluating the organization's efforts to make documents available for public consultation. Additionally, **GOB3**, the participation in planning indicator, includes two variables: DPA, which measures the number of participation mechanisms preceding the public consultation of the water management plan, and DPAQI, which assesses the number of active participation instruments during the formulation of significant topics. Lastly, GOB4, the type of participation indicator, combines four variables: ApprochePublic, examining the chosen approach of managers during the consultation phase; Participation souhaite, assessing the type of exchange in participation meetings; diversité, measuring the diversity of participation mechanisms during public consultations, and Cible, evaluating the target audience of the participation process during the development of the water management plan.

More detailed information about the calculation methodologies of the indicators discussed above is provided in Annex of this deliverable.

5.3 Water demand reliability indicators

Indicators of water demand reliability play a crucial role in assessing the stability and dependability of water supply systems. One key indicator is the reliability of water demands, which measures the probability of being in a satisfactory state without experiencing failure or water shortage. It provides valuable insights into the frequency of occurrence of failure situations and helps evaluate the overall performance and resilience of water supply systems. The reliability indicator quantifies the probability of meeting water demand consistently over time. A higher reliability indicates a lower risk of failure or water shortage, demonstrating the robustness and effectiveness of the water supply system.

These indicators for assessing water demand reliability can be categorized into different types, each providing specific insights into the stability and performance of water supply systems. These indicators are valuable tools for decision-makers to evaluate and monitor water reliability.

The first type of indicator is the **monthly water reliability indicator**. It measures the frequency of monthly failures in meeting the water demand. A failure occurs when the monthly demand is not adequately satisfied within a month. To determine the failure, a threshold value of A% is set, where A represents a percentage (e.g., A=5%). The calculation of the Monthly Water Demand Reliability Indicator involves determining the percentage of months without failure out of the total number of months.

The **annual water demand reliability indicator** is a crucial metric that assesses the frequency of failures in meeting the water demand throughout the year. A failure occurs when the supply of water is not satisfactory to fulfill the demand during that particular year. This indicator takes into account two specific definitions of failure. Firstly, an annual failure is recorded if the deficit in water supply during any given month exceeds a certain threshold, represented by B% (B=30%). Secondly, an annual failure is noted if the total cumulative shortfall in water supply over the entire year exceeds a specific threshold, represented by C% (C=15%).

The **volumetric water reliability indicator** provides a quantifiable representation of the reliability of water supply in terms of volume. The indicator is calculated by dividing the actual volume of water supplied by the volume of water demanded, yielding a percentage value. This value indicates the extent to which the water demand is being met on average. Reference values for volumetric reliability typically range between 90% and 95%, representing the desired level of reliability in terms of meeting the volumetric water demands.

The **indicators proposed by the Utah Division of Water Resources** are based on reliability criteria that consider different deficits for different time periods. They are based on accumulated deficits over 1 year, 2 years, and 10 years. The indicator provides two possible outcomes: "Meets criteria" or "Does not meet criteria".

The "Does not meet criteria" outcome occurs when one of the following three circumstances is met:

1. The maximum deficit in a single year exceeds D% of the annual demand.
2. The maximum deficit over two consecutive years exceeds E% of the annual demand.
3. The maximum deficit over ten consecutive years exceeds F% of the annual demand.

This criterion is linked to a historical time series, which raises concerns about its representativeness, and longer time series may worsen the results by considering the worst "historical" drought. For Spain, the reference values set for this indicator are D=50, E=75, and F=100.

The Spanish Ministry's Ministerial Order of September 24, 1992, adopts the UTAH DWR criteria for the Basin Hydrological Plans. The implementation of this approach requires historical data spanning at least from 1940 to 1996 due to the drought events in the 1990s. The UTAH-type indicator introduces a more stringent evaluation of water reliability, aiming to reduce the intensity of failures in the worst years, consecutive two-year failures, and overall vulnerability by reducing the magnitude of the long-term failure. By employing the UTAH-type indicator in decision-making, water resource managers and planners can gain valuable insights into the resilience and reliability of water supply systems over different time scales, leading to more effective strategies for water resources management and drought risk mitigation.

Finally, a novel methodology has been recently proposed that combines water demand reliability indicators with hydrological and habitat indicators (Ghannem et al., 2023). This integrated approach promotes the sustainable management of water resources and can be used to optimize the potential benefits of MAR initiatives.

5.4 Feasibility maps indicators for MAR decision-making

Feasibility maps serve as valuable indicators in the decision-making process for MAR projects. These maps provide a visual representation of the suitability and potential feasibility of different regions for MAR implementation. By integrating various parameters and criteria, feasibility maps offer decision-makers a clear understanding of the most favorable locations for MAR projects.

Feasibility maps act as indicators by highlighting areas that meet the necessary conditions for successful MAR implementation. They consider factors such as hydrogeological characteristics, water availability, demand for groundwater-dependent services, and non-physical considerations like economic viability, social acceptance, environmental impacts, and legal constraints.

The development of feasibility maps involves an interactive process that engages experts and stakeholders. The experts provide input and insights, linking physical and non-physical criteria, while stakeholders contribute their perceptions of MAR. Through this collaborative approach, the methodology generates a final set of weighted criteria used to map the potential feasibility of MAR in specific geographic regions. It is based on three fundamental pillars: assessing the demand for groundwater-dependent services, evaluating the availability of conventional and non-conventional water sources for MAR, and analyzing the intrinsic hydrogeological characteristics of potential regions.

Decision-makers can utilize feasibility maps to assess and compare different regions based on their potential for MAR. The maps provide a spatial perspective, allowing stakeholders to identify areas with optimal conditions for groundwater recharge and recovery. By visualizing the suitability of various regions, decision makers can prioritize their efforts and allocate resources effectively.

Moreover, feasibility maps offer a valuable tool for communication and stakeholder engagement. They facilitate discussions among stakeholders, enabling a shared understanding of the potential benefits and challenges associated with MAR projects. By presenting clear and objective indicators, feasibility maps foster informed decision making and support consensus building among stakeholders.

The use of feasibility maps as indicators also promotes transparency and accountability in the decision-making process. By documenting the criteria, data sources, and methodologies used in developing the maps, decision makers can ensure that their decisions are based on a robust and systematic assessment. Feasibility maps enable stakeholders to evaluate the validity and reliability of the indicators, enhancing trust and credibility in the decision-making process.

Overall, feasibility maps serve as powerful indicators that guide decision-makers in identifying suitable locations for MAR projects. As methodologies with the degree of feasibility acting as a spatial indicator, these maps provide a comprehensive overview of the potential feasibility of different regions, incorporating both physical and non-physical considerations. By leveraging these maps, decision makers can make informed choices, optimize resource allocation, foster stakeholder engagement, and ultimately contribute to the successful implementation of MAR projects for sustainable water management. The spatial representation of the degree of feasibility enables a clear identification of areas where MAR projects are more likely to succeed, allowing for efficient targeting of efforts and resources.

6. Overview of legal aspects of managed aquifer recharge

6.1 Legal framework for managed aquifer recharge in European water policy

The European Union's Directive 2000/60/EC, known as the Water Framework Directive, aims to establish a comprehensive framework for the protection of continental surface waters, transitional waters, coastal waters, and groundwater. It sets out various environmental objectives, including the prevention or limitation of pollutants' entry and the deterioration of all water bodies, the protection, improvement, and regeneration of groundwater, ensuring a balance between extraction and replenishment for achieving good status, and reversing any significant and sustained increase in pollutant concentration (EU, 2000).

However, the term "artificial recharge" is not included in the definitions provided by the directive. Article 11 of the directive outlines the basic measures of the action program required to achieve the environmental objectives, including control measures for MAR, which necessitate prior authorization.

Furthermore, Directive 2006/118/EC specifically focuses on the protection of groundwater against pollution and deterioration. Article 6 addresses measures to prevent or limit pollutant entries into groundwater, aligned with the environmental objectives stated in Article 4 of the Water Framework Directive. However, it also lacks a specific definition of MAR. Member states may exempt authorized MAR or increases in recharge from the measures outlined in Article 6, as per Article 11(3)(f) of Directive 2000/60/EC. Nonetheless, the terms "artificial recharge" or "managed aquifer recharge" remain undefined (EU, 2006).

6.2 Case of Spain and associated issues

Managed aquifer recharge has minimal legal treatment in Spanish legislation, as it is not explicitly defined in any of the current legal texts such as the Water Framework Directive, Groundwater Directive, and Spanish Water Law. However, it is essential to note that some regulations do address certain aspects of MAR. For instance, the Spanish Regulations for Water Reuse (Royal Decree 1620/2007) establish water quality criteria specifically for two types of MAR systems: percolation through ponds and injection through wells. The only existing definition is found in the regional Water Law of Andalucía, which could easily be adopted at the national level. This law also regulates the authorization process for recharge projects and provides legal safeguards for ongoing projects, which are all noteworthy aspects that should be incorporated into national legislation. Similarly, the implementing regulations of the Water Public Domain and Water Planning do not offer significant provisions concerning MAR. The National Water Plan also lacks specific provisions related to MAR, except for a list of four investment actions that were supposed to be implemented between 2001 and 2008 but have not been realized to date. Only the Water Plans of the Guadalquivir, Duero, and Baleares Islands basins include some regulatory aspects regarding MAR. The Guadalquivir Water Plan includes 17 recharge actions to be implemented, while the Duero Water Plan considers MAR projects in the province of Segovia as special actions rather than discharges. Lastly, the Baleares Islands plan establishes reserved flow rates from recharge for public administrations and provides guidelines for implementing recharge projects or barriers against seawater intrusion (Orden Gómez, 2017).

Based on the Spanish regulations, the following points are clear:

- Managed aquifer recharge is considered discharge according to the literal interpretation of Article 100 of the Water Law.
- It is subject to a concessional regime for the recharged volumes, as stated in Article 59 of the aforementioned law.
- Authorization for discharges is required, as stated in Article 257 of the Hydraulic Public Domain Regulations, which modifies the absolute prohibition of discharges into the hydraulic public domain mentioned in Article 100 of the Water Law.
- Article 257 of the Hydraulic Public Domain Regulations also requires the submission of a hydrogeological study demonstrating the harmlessness of the recharge project, although the concept of harmlessness lacks a legal definition.
- According to Article 299 of the Hydraulic Public Domain Regulations, users of an artificially recharged aquifer are subject to the payment of regulation fees.

In conclusion, the legal treatment of MAR in Spain is currently insufficient and lacks clarity. The absence of a comprehensive definition and the limited provisions in national legislation pose significant challenges for implementing recharge projects. The existing regulations focus primarily on considering recharge as a discharge, subjecting it to a concessional regime and requiring authorization and hydrogeological studies to demonstrate its harmlessness. However, these concepts and requirements lack precise legal definitions. Urgent legislative modifications are necessary to establish a clear definition of MAR, recognize it as an integral part of water resource management, and provide a unified framework for all recharge projects in Spain. It is crucial for Spain to learn from other countries (the Netherlands, Italy, Mexico, Australia, and the United States) and streamline its legislation to facilitate the execution of MAR initiatives and ensure sustainable water management practice.

6.3 Case of Portugal and associated issues

There is no specific regulation for MAR in Portugal. Nevertheless, there are two recent resolutions from the Parliament about MAR: Resolução da Assembleia da República n.º 86/2022 - Recommends that the Government encourages managed aquifer recharge to reinforce water efficiency, and the Resolução da Assembleia da República n.º 87/2022 - Recommends the Government to increase the reuse of treated wastewater. Nevertheless, the only existing decree that establishes the legal regime for the production of water for reuse obtained from the waste water treatment, as well as its use (Decreto-Lei 119/2019) does not specifically consider MAR. The watershed management plans also refer to the use of MAR, but no specific actions are known.

The MAR systems where natural recharge is enhanced are generally accepted (e.g., infiltration basins typically built to decrease flood impacts) and no restrictions are known.

For the MAR systems using alternative water sources, such as treated wastewater, as the source of water for recharge, the water quality must comply with the quality standards listed in the Annex I of Directive 91/271/EEC (which regulates the discharge of wastewater, transposed into Decreto-Lei 152/97). The proponent must have a permit from the APA (Portuguese Water Authority) that defines the necessary Environmental Impact Assessment (EIA) studies to be able to acquire a license and the necessary monitoring procedures (before and after MAR).

Based on the Portuguese regulations, the following points are clear:

- MAR systems consisting of natural recharge enhancement are currently not being considered MAR, therefore they are not subject to an EIA.
- MAR systems using alternative water sources are considered a discharge according to Decreto-Lei 152/97. A license for discharges and the necessary monitoring procedures can be obtained if the hydrogeological studies prove the harmlessness of the recharge project, although the concept of harmlessness lacks a legal definition.

The conclusions written for Spain totally fit to the Portuguese reality.

6.4 Case of Cyprus and associated issues

According to the national authorities (Hadjigeorgiou, 2019), the policy for Water Reuse aims on:

- Full exploitation of treated water for decreasing the necessity for constructing additional desalinization plants.
- Formulation of national regulations taking into account human health, agronomical and environmental aspects which are more stringent than Directive 91/271/EEC.
- High-quality of tertiary treated water irrespective of its use (agricultural, and landscape irrigation/golf courses, recharge of aquifers)

Regarding the recharge assessment of treated wastewater, it is done according to Wastewater Treatment Plant (WWTP) threshold limits, along with the Directives 2006/118/EC and 2014/80/EU for groundwater, and the consolidated Directive 2008/105/EC, Directive2013/39/EU for priority substances in surface water.

Furthermore, the groundwater quality is monitored regularly in accordance with the Discharge Permit regulated by:

- The Environmental Impact Assessment Law (No. 140 (I)/2005),
- The Water Pollution Control Laws (106(I)/2002 to 2009),
- The Water Pollution Control (Discharge of Urban Wastewater) Regulations of 2003 (No. 772/2003),

Whereas the degree of tertiary treatment is determined based on the requirements of Directive 91/271/EEC on the Treatment of Urban Wastewater.

Overall, the legal treatment of intentional groundwater recharge in Cyprus is insufficient and lacks clarity since there are currently no regulations regarding artificial recharge.

6.5 Case of Tunisia and associated issues

In Tunisia, specific legislation on MAR is limited or absent. It was only once recognized by the water code (1975) in its sixth chapter, Article 87, as a beneficial measure for water resources development. MAR is administratively belonging to the activities of the General Directorate of Water Resources in the Ministry of Agriculture, Hydraulic Resources and Fisheries (MAHRF). The Sub-directorate of "Artificial recharge" is responsible for planning new MAR schemes, monitoring, and management of the existing MAR projects. On the regional scale, MAR is a sub-activity of the water resources department at every regional commissariat of agricultural development (CRDA). MAR is strictly depending on the recharge water availability, which is planned by the Bureau of Planification and Hydraulic Equilibrium (BPEH) in the MAHRF and allocated mainly by the National Company of North Water Canal and adductions exploitation (SECADENORD) and the existing dams for conventional water. Unconventional water, especially treated wastewater is provided by WWTPs belonging to the National Sanitation Utility (ONAS). Other administrations are involved in MAR monitoring especially in the case of TWW reuse: principally the National Agency of Environmental Protection (ANPE) and the directions of hygiene and environment protection (Ministry of Public Health).

7. Overview of MAR applications: challenges and lessons learned

7.1 Challenges and initiatives in MAR in Spain

Managed recharge of aquifers is an essential approach for increasing water availability and improving water quality. However, its implementation in Spain faces various challenges, including technical, economic, environmental, social, and legal considerations. At present, the volumes of water recharged through MAR in Spain account for only 7% of total groundwater usage (Dillon et al., 2019). Current legislation, such as the Water Framework Directive (DMA) and the Consolidated Text of the Water Law (TRLA), lacks clear definitions and provisions for MAR, hindering its widespread adoption. Despite these obstacles, several initiatives are underway in different hydrographic basins across Spain.

Analyzing the third-cycle water management plans for different river basins, several MAR initiatives have been identified. In the Duero river basin, the El Carracillo project has demonstrated successful MAR using diverted water from the Cega River. This ongoing project involves expanding the recharge and usage zones, requiring modifications to the concession. Additionally, studies have been conducted for potential long-term recharge of the Valduerna aquifer using water from the Duerna River (Martínez Cortina, 2022).

In the Tajo river basin, the Canal de Isabel II has allocated a budget for various groundwater-related projects, including managed recharge of the Madrid detrital aquifer. Further details regarding the specific characteristics and investment of the "Plan Recarga" are currently unavailable. The Guadalquivir river basin has identified several MAR projects as priority studies. These initiatives aim to increase water supply for urban and agricultural purposes, address overexploitation issues, mitigate drought effects, and preserve ecologically important wetlands. Noteworthy projects include the Calahorra-Huéneja corridor, Úbeda, Sevilla-Carmona, Bedmar-Jódar, Gracia-Ventisquero, Larva, Baza-Freila-Zújar, Lora del Río-Hornachuelos, and Vega de Granada. The existing Marbella-Estepona MAR project in the Mediterranean Andalusian basins showcases ongoing efforts to replenish aquifers using spring water from the Sierra de las Nieves. The project serves as a promising example of successful artificial recharge implementation (Martínez Cortina, 2022).

The current state of legislation regarding MAR highlights the need for better consideration and revision, particularly in the water law. Addressing the challenges associated with MAR requires comprehensive frameworks that encompass technical, environmental, economic, and legal aspects, ensuring the sustainable management of water resources.

Belcaire pond case study:

The study area is located within the hydrographic basin of the Júcar River, specifically in the sub-basin of the Belcaire River, bordered to the north by the sub-basin of the Mijares River and to the south by the sub-basin of the Palancia River. An analysis of the water balance in the area over the past years indicates a renewable groundwater resource and reused water sum of 9 hm^3/year, while the average demand is 16.82 hm^3/year, resulting in an overexploitation of 7.82 hm^3/year.

Among the challenges faced in the area are the high water demand in the irrigation areas of Castellon, the advancement of marine intrusion in the Rambleta aquifer, and the increasing number of saline wells in the aquifer. Currently, there is a lack of regulation for the water flowing through the Belcaire River, resulting in an estimated discharge of 6 hm^3/year into the sea. This prevents the percolation of water into the aquifer and its corresponding recharge.

The objective of the proposed intervention is to recharge the La Rambleta aquifer using the surplus water from the Belcaire River. For effective recharge, a continuous and controlled inflow of relatively small volumes is required. Therefore, a regulation system is necessary to retain flood volumes and allow for delayed recharge over time. The karstic system in the area, particularly the well-known San José Caves, acts as a natural regulator of floods by infiltrating excess water into its cavities and gradually discharging it over the following days. This underground flow significantly improves the water quality by facilitating filtration and reducing suspended matter.

The Belcaire pond plays a crucial role in the project. The river watershed covers an area of 96 km^2, and its inputs are the Barranco de San José and the Rambla Cerverola. The pond is supplied through a diversion weir, and its different phases of development have spanned several years. The project includes the regulation of winter surplus water from the Belcaire River, and it has undergone various stages, including the drafting of a regulation works project, an Environmental Impact Assessment (EIA), public disclosure, inclusion in the Priority Hydrological Plan (PHN), and signing of management agreements.

Furthermore, a pilot aquifer recharge test was conducted between 2013 and 2014, which involved the recharge of 314,613 m^3 of water into the aquifer through an average flow of 21.46 l/s. Additionally, the General Irrigation Community (CGR) of Vall d'Uixó requested provisional use of the pond volume for irrigation due to the drought situation, which was authorized with a maximum volume of 420,000 m^3.

In the present situation, the emptying phase of the commissioning program is nearing completion. The water level in the pond is at 59.56 m a.s.l., with an impounded volume of 674,996 m^3. The available volume above 58 m a.s.l. is 247,961.07 m^3. It should be noted that the provisional authorization issued by the Júcar River Basin Agency (CHJ) for the CGR has expired, and Waters of the Mediterranean Basins company (ACUAMED) has requested authorization for the emptying of the reservoir through artificial recharge to the aquifer and simultaneous supply to the CGR. The joint supply is sought to minimize the time required for the commissioning program and the normal operation of the works.

The Belcaire Pond project serves as an example of a MAR initiative that faced challenges in achieving efficient aquifer recharge. These challenges can be attributed to the physical characteristics of the area, as well as economic and governance factors, primarily the limited availability of water resources. This highlights the importance of conducting thorough feasibility assessments for MAR projects, considering their purpose, whether it be urban/agricultural water supply or mitigating saltwater intrusion.

In light of the aforementioned challenges, it becomes crucial to propose effective operating rules that prioritize either recharge or direct water use based on the prevailing conditions. This adaptive approach ensures that the limited water resources are utilized optimally and addresses the specific needs of the situation at hand. By establishing clear operating rules, decision makers can navigate the complexities of water management and strike a balance between recharge and direct use, thus maximizing the benefits of MAR projects.

Furthermore, the Belcaire Pond project underscores the need for a comprehensive evaluation of the economic and governance aspects associated with MAR initiatives. Adequate consideration of these factors is vital for ensuring the long-term viability and success of MAR projects, ultimately contributing to sustainable water resource management in the region.

In conclusion, while the Belcaire Pond project faced challenges in achieving efficient aquifer recharge, it highlights the importance of conducting feasibility assessments, proposing effective operating rules, and considering economic and governance factors when implementing MAR projects. By addressing these aspects, future MAR initiatives can overcome obstacles and effectively contribute to enhancing water availability, mitigating water intrusion, and supporting sustainable water management practices.

Algar reservoir case study:

The Algar reservoir, with a capacity of 6 hm^3, serves multiple purposes including increasing surface resources, recharging aquifers, reducing groundwater withdrawals, and flood control. While the primary objective of the reservoir was to increase surface resources, the high rates of infiltration have shifted its focus towards recharging the Algar-Quart aquifer. However, one of the main challenges faced in groundwater recharge was the lack of data about the aquifers.

According to a hydrological report on aquifer recharge induced by the Algar dam and a proposed monitoring plan, several conclusions were drawn. Accurately determining the infiltration in the reservoir was challenging due to the uncertainty surrounding input and output data, especially in calculating lateral transfers between aquifers. Nonetheless, the increase in infiltration into the aquifer had several positive impacts, including correcting temporary overexploitation, improving energy efficiency in groundwater exploitation, and increasing water availability in the Quart Spring.

During the observation period from 1/04/2012 to 1/07/2019, the average infiltration flow in the reservoir basin was estimated at around 0.57 m^3/s. This translates to an average supply to the aquifer of approximately 17.94 hm^3, with peak values leading to periods of reservoir filling. The extraordinary infiltration contributions from the reservoir helped mitigate the effects of overexploitation and would eventually drain through the Quart Spring after remaining in the aquifer for a certain period.

To monitor the recharge induced by the Algar reservoir, several measures were proposed. These include constructing a gauging station in the Regajo-Algar region to measure inflows from the Palancia River outside the reservoir's influence area, establishing two gauging stations downstream of the dam on the Palancia River (one immediately downstream and the other at Estivella) to determine specific infiltration areas, and conducting periodic infiltration tests for different reservoir water levels lasting 48 hours.

In terms of water discharge, subway transfers to nearby aquifers constitute approximately 5.3% of the total annual average discharge, amounting to an estimated 1.25 hm^3/year in an average year. The technical direction of the CHJ aims to minimize groundwater usage, aligning with a strategy of reducing reliance on groundwater.

The Algar reservoir case study serves as a conclusive example of the importance and feasibility of MAR projects. Initially not designed for MAR purposes, the reservoir ultimately became a crucial contributor to aquifer recharge. The successful recharge of the Algar-Quart aquifer through the dam itself underscores the potential for MAR in addressing various water management objectives. The implementation of the Algar reservoir project required the establishment of effective management rules to govern the recharge process. The dam's strategic location after the intake of the Sagunto irrigation ditch ensured that decisions upstream were not influenced, demonstrating the importance of conjunctive water use, and considering MAR objectives within the broader context of water management.

Overall, the Algar reservoir case study reinforces the significance of considering both the objectives of MAR and the feasibility of implementation in water management strategies. It exemplifies how repurposing existing infrastructure can contribute to sustainable water resource management and address the increasing demands for water. The successful integration of MAR objectives into the broader context of water management can pave the way for effective and efficient water resource utilization, benefiting both human needs and the environment.

7.2 MAR applications in Portugal

Portugal, like many other countries, faces challenges related to water scarcity and quality. MAR can be an effective strategy to address these challenges by replenishing depleted aquifers, improving water storage and quality, and enhancing water supply reliability.

While no specific information on the status of MAR projects in Portugal exists, some work and new infrastructures has been done, typically in the MAR research projects GABARDINE, MARSOL and now AGREEMAR. A synthesis of the site's descriptions and results achieved can be found in http://www.marsol.eu/files/marsol_d4-5_mar-south-portugal_final-report.pdf, and a synthesis of this in the article of Leitão et al. (2016).

Under GABARDINE and MARSOL projects, three deep infiltration basins have been constructed in the Seco riverbed (400 m^2 with 7 m average depth) to promote the infiltration of naturally occurring water in the river (which has running water in about 1/6 of the year, typically as stormwater runoff), allowing to improve the chemical status of the nitrate vulnerable zone of Campina de Faro aquifer, Algarve region. The overall maximum infiltration capacity was calculated as 21,5 m^3/h. These techniques allow the water to undergo natural filtration processes and recharge the underlying aquifer. Also, the injection capacity of existing large diameter wells has been studied in that region, aiming to contribute to decrease the nitrate content. The maximum infiltration capacity of each well was calculated as 35 m^3/h (the high heads achieved during infiltration allow these high values, when compared to the basins). Numerical models of the area exist to simulate the effects of current and future scenarios.

The first soil-aquifer treatment (SAT-MAR) system was studied during MARSOL project, where treated wastewater was used after a secondary treatment in São Bartolomeu de Messines, Algarve region. Its annual flow is 0.262 to 0.418 x 10^6 m^3. This system is composed of two sequential basins where both aerobic and anaerobic conditions can be created to improve the removal performance of contaminants, such as pharmaceutical compounds and nutrients. The system can be considered MAR since the water, after treatment, goes to the same small stream that is used to receive the secondary treatment, being this stream influent over a karstic system (Querença-Silves aquifer, Algarve region). However, the SAT-MAR basins are impervious. The system was used for research purposes only.

Comporta Wastewater Treatment Plant (WWTP, dimensioned to treat wastewater from a population of around 2,500 inhabitants-equivalent in high season and 589 inhabitants-equivalent in low season), in Alentejo region, is the 1st example of an official MAR system running in Portugal since October 1st, 2021. It is a case-study site for the AGREEMAR project. The WWTP is equipped with a technologically advanced treatment system, including primary, biological treatment and additional disinfection to produce water for reuse and treatment of sludge by dehydration. The daily volume of secondary treated wastewater discharged in the current MAR system, composed of four infiltration ponds, varies from 110 to 190 m^3, and it is presented as an alternative to the commonly implemented method of direct discharge of treated effluents into surface water bodies. The region in which it operates has Sado estuarine ecosystem, a sensitive area classified as a Nature Reserve, and is located over the Left-Margin Tejo-Sado aquifer (the largest aquifer of the Iberian Peninsula with 6,875.44 km^2).

There are other examples of naturally occurring MAR, such as Cerro do Bardo site, located in the karstic aquifer of Querença-Silves aquifer, Algarve region. This area was studied under MARSOL project. The infiltration capacity in one large well tested in the site was calculated as 125 m^3/h.

7.3 MAR applications in Cyprus

Cyprus suffers from a chronic water shortage due to the combined effects of climatic conditions, resulting in extensive droughts, and overexploitation of the existing water sources to satisfy the growing demand.

One of the measures promoted by the authorities to tackle this issue is the reuse of treated effluent from the urban waste-water treatment plants in irrigation and aquifers recharge. Aquifers are used as storage reservoirs mainly in the winter, whereas water is extracted and used during the irrigation period. Some representative examples in Cyprus are the Akrotiri Aquifer (in Limassol) and the Ezousa Aquifer (in Paphos), which are also enriched with tertiary treated water.

Two MAR systems are currently in operation in Cyprus. The first one is in Paphos and enriches the Ezousa alluvial aquifer with tertiary treatment water since February 2004 based on soil-aquifer treatment (SAT) with the aim of providing water supplies mainly for irrigation purposes while mitigating the adverse effects that exist in the area due to geogenic activities (high concentration of sulphates and Boron), salinization (seawater intrusion and overexploitation of groundwater) and anthropogenic activities (nitrification, high concentration of pesticides, sewages). About 70 % of total groundwater abstraction is used for agricultural purposes due to the intense agricultural activities that are present in the area, whereas the remaining 30% of groundwater abstraction is used for domestic and industrial purposes, such as golf fields and tourism facilities (Christodoulou et al., 2007). As seen in Figure 1, the operation of the artificial scheme can be splitted into six steps (Panagiotou et al., 2023).

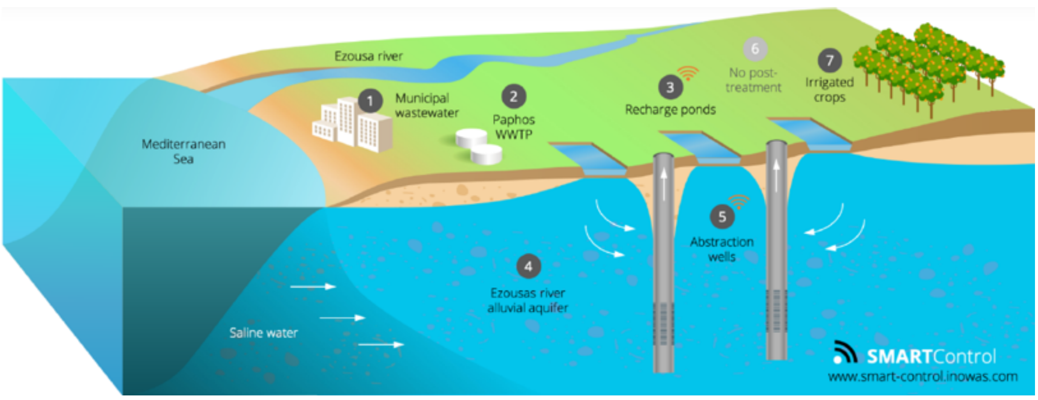

Figure 1. Schematic overview of MAR components of Ezousa SAT system (Panagiotou et al., 2023)

Particularly, raw wastewater is collected from the urban area (Step 1) and is discharged to Paphos Wastewater Treatment Plant (WWTP). There, the influent is subject to three main treatment processes (Step 2): primary, secondary, and tertiary. Then, the effluent is distributed through pipeline networks to infiltration ponds (Step 3), from which it percolates until it reaches the saturated zone and mixed with the ambient groundwater (Step 4). Groundwater is extracted from wells which are located downstream of the recharge ponds (Step 5), and then distributed through a canal (Step 6) at a ratio of 1:20 (groundwater to dam water).

According to the national guidelines, groundwater and surface samples are collected three times per year from eleven locations that are selected for monitoring the surface and groundwater quality downstream and upstream of the recharge ponds for five groups of substances (organics, pesticides, microbiological, nutrition, minerals).

The second MAR scheme is located in Limassol district and enriches the Akrotiri coastal alluvial aquifer with tertiary treatment since February 2016. The Akrotiri aquifer is the third largest continuous and most important porous aquifer of Cyprus and is in the southern part of Cyprus. As in Ezousa case, the operation of the MAR scheme is expected to mitigate the deterioration of the groundwater quality, mainly due to the intense anthropogenic activities that exist in the area (agricultural, industrial), resulting in seawater intrusion and potential contamination of nearby drinking wells that exist in the area. In this project, two complexes of enrichment ponds are used to store the recycled water that are located in the Kouris basin. More specifically, 17 enrichment ponds (or lakes) have been constructed along the Kouris River, comprising a total area of 56,000 m^2.

Overall, the national authorities recognize the usefulness of artificial recharge on addressing the existing challenges (Hadjigeorgiou, 2019), which can be summarized as follow:

- Need to intensify the efforts on satisfying the increasing water demand and managing the growing water shortage.
- Augment the production of treated wastewater to sustain major water sectors such as agriculture, industry and domestic.
- Continue the intentional recharge of alluvial aquifers via treated water that satisfies the quality standards for storage and recovery purposes.

7.4 MAR applications in Tunisia

In Tunisia, MAR has become a priority in water management plans since 1970s. Since this date, several techniques are adopted and most of them are using different setups to infiltrate surface water into aquifers. The commonly used techniques are injection in dry well, dam water release, infiltration pond, soil aquifer treatment and percolation tank. The total recharge amount in Tunisia is estimated to range between 14 and 66 million m^3/y in the period 1992-2015 (DGRE, 2015). The choice of MAR techniques was not based on solid scientific knowledge. In fact, most of the implemented MAR projects were a response to the pressure of overexploitation and quantitative and qualitative groundwater deterioration only; there is no previous suitability mapping procedure before projects implementation. Consequently, a clear sustainability problem is affecting most of MAR projects in Tunisia. For instance, the MAR project in Korba aquifer, CapBon peninsula (NE of Tunisia) using infiltration basins of treated wastewater did not exceed 7 years lifetime (2008 – 2015) because of clogging, lack of treated wastewater and limited size of the MAR infrastructure compared to the existing piezometric depression (Gaaloul et al, 2012; Mekni and Souissi, 2016). Also, the MAR project in Khairat watershed (coastal region in NE of Tunisia) using released dam water and in-channel modifications was almost ineffective just after 5 years implementation (2006 – 2011) because the wrong choice and dimensioning of check dams and their destruction after the 2011 flooding (Belghith Triki et al, 2014). MAR is taken into consideration as mighty interest in case of coastal aquifers which usually supply increasingly water demand for irrigation and drinking purposes. However, the high complexity and high heterogeneity of the coastal region makes it hard to locate and determine suitable areas to implement MAR projects as possible remedy to overexploitation and quality deterioration. Additional information is needed to identify potential MAR locations and increase the results validation, such as field observations, and referring to databases of thematic layers like soil, geology, land use and land cover, slope, drainage, and lineament density. As a result, application of MAR is still marginal in Tunisian coastal aquifers and the current state of knowledge on MAR in these areas is limited. To better understand the potential for MAR in these zones, it is prudent to understand which MAR approaches can be applied in coastal and semi-arid areas in general.

8. Evaluation of the strengths and limitations of existing MAR approaches

As MAR gains recognition worldwide, it is essential to evaluate the strengths and limitations of existing approaches to enhance our understanding and refine future implementation strategies. It is important to assess the effectiveness, benefits, and challenges associated with different MAR approaches based on the analysis of relevant case studies.

8.1 Strengths of existing MAR approaches

- **Water resource enhancement**: MAR projects provide a means to augment water resources by capturing surplus water during wet periods and storing it in aquifers. This approach contributes to increased water availability during dry periods, mitigating the effects of droughts and ensuring long-term water security.
- **Aquifer recharge and groundwater sustainability**: MAR facilitates the replenishment of aquifers, maintaining or restoring groundwater levels. By recharging aquifers, MAR projects help counterbalance excessive groundwater withdrawals, combating overexploitation and minimizing the risk of subsidence and saltwater intrusion.
- **Integration with existing infrastructure**: Utilizing existing reservoirs, dams, and infrastructure for MAR purposes optimizes resources and minimizes construction costs. The Algar reservoir case study exemplifies this integration, where the reservoir serves as an effective tool for artificial aquifer recharge without the need for extensive additional infrastructure.
- **Conjunctive water management**: MAR projects promote conjunctive use, enabling the integration of surface water and groundwater resources. By strategically managing water sources, MAR provides flexibility in water allocation, allowing for sustainable and coordinated water management.

8.2 Limitations and challenges of existing MAR approaches

- **Data and monitoring**: One of the significant challenges in MAR implementation is the availability and accuracy of data on aquifer characteristics, hydrological processes, and water quality. Insufficient data hinders precise estimation of recharge rates, potential impacts, and long-term sustainability, necessitating robust monitoring programs and comprehensive data collection.
- **Technical and engineering constraints**: The success of MAR projects depends on the selection of appropriate recharge techniques, considering site-specific conditions and hydrogeological characteristics. Technical challenges can arise due to subsurface heterogeneity, clogging of recharge structures, and the potential for groundwater contamination if not adequately managed.
- **Governance and policy frameworks**: Effective MAR implementation requires supportive governance structures, regulatory frameworks, and clear policy guidelines. Challenges may arise in securing necessary permits, addressing legal aspects, and establishing responsibilities among stakeholders. Ensuring stakeholder engagement and cooperation is vital for successful MAR projects.
- **Economic viability**: The economic feasibility of MAR projects must be carefully evaluated, considering capital and operational costs, long-term maintenance requirements, and the potential benefits gained. Cost-effectiveness analysis, along with the consideration of alternative water management strategies, is crucial in decision-making processes.

Existing approaches for MAR demonstrate significant strengths in enhancing water resource management, promoting aquifer recharge, and integrating surface and groundwater systems. However, challenges related to data availability, technical constraints, governance frameworks, and economic viability require careful consideration.

To address these limitations, it is important to focus on improving data collection and monitoring networks, enhancing technical designs and operational strategies, developing robust governance frameworks, and conducting comprehensive cost-benefit analyses. Additionally, the development and utilization of appropriate indicators in this context will play a crucial role in monitoring MAR projects, assessing their effectiveness, and providing valuable insights to decision makers. These indicators will enable better evaluation of recharge rates, groundwater levels, water quality, and the overall performance of MAR systems.

By evaluating the strengths and limitations of existing MAR approaches and employing suitable indicators, we can refine and optimize future implementations, leading to more sustainable and effective water resource management practices.

9. Summary and conclusions

The present report provides a preliminary analysis of indicators and methodologies for decision-making in the context of integrated water resources management, with a particular focus on MAR projects. The evaluation of existing approaches reveals both strengths and limitations that need to be considered for effective implementation and monitoring of MAR initiatives.

One of the key findings of this analysis is the importance of adopting a conjunctive use approach to enhance the implementation of MAR projects. By considering the integrated management of both surface and groundwater resources, decision makers can optimize water allocation and maximize the benefits of MAR in addressing water scarcity and improving water availability.

It is essential to recognize that MAR goes beyond direct methods of injecting water into aquifers. It also includes the concept of induced recharge, where aquifers are naturally recharged due to reduced withdrawals or changes in water management practices. This comprehensive understanding of recharge and recovery is crucial to ensure the overall health and balance of aquifer systems. While MAR projects can play a significant role in recharging aquifers and contributing to their recovery, it is important to explore alternative conjunctive water use options as well. These options aim to minimize the expenses associated with the implementation of MAR projects while still achieving sustainable water management outcomes.

By considering alternative conjunctive water use strategies, decision makers can identify opportunities to optimize water allocation and utilization. For example, implementing water conservation measures, such as improving irrigation efficiency or adopting innovative agricultural practices, can reduce water demands and subsequently result in reduced aquifer withdrawals. This reduction in withdrawals, in turn, can lead to natural recharge processes and aquifer recovery.

Furthermore, exploring non-conventional water sources, such as treated wastewater or desalinated water, for appropriate uses can help reduce the reliance on traditional freshwater sources and minimize the need for extensive artificial recharge efforts. By integrating these alternative water sources into the water supply system, the pressure on aquifers can be reduced, allowing them to naturally recover and maintain their long-term sustainability.

It is important to note that while MAR projects offer valuable benefits in terms of water storage and availability, they also come with associated costs and potential environmental impacts. Therefore, a comprehensive evaluation of the feasibility and cost-effectiveness of MAR projects should be conducted, considering the specific hydrogeological conditions, water demands, and socio-economic factors of the region.

To facilitate decision-making, the use of Decision Support Systems (DSS) and indicators is crucial. Detailed aquifer models, complemented by DSS, enable a holistic understanding of the impacts of MAR projects at both local and basin scales. Indicators provide a synthesized representation of the project's effectiveness and can be used to monitor progress and inform decision-makers about the success of MAR initiatives.

Environmental indicators, such as those assessing water supply sustainability, hydrological alteration, and agricultural water sustainability, provide valuable insights into the ecological impacts and sustainability of water management practices.

Socio-economic indicators play a crucial role in understanding the relationship between water resources and economic activities. They assess water productivity in various sectors, including agriculture, industry, and services, as well as the intensity of water use in relation to employment. These indicators contribute to informed decision-making by considering the economic aspects of water allocation.

Governance indicators offer valuable insights into the effectiveness of water resource management practices. They assess aspects such as transparency, public participation, and the inclusion of diverse stakeholders in decision-making processes. These indicators help evaluate the governance practices within water management and promote transparent and inclusive approaches.

The analysis of existing approaches for MAR projects underscores the significance of adopting a conjunctive use approach, considering the recharge and recovery of aquifers, and utilizing indicators for effective decision-making. The proposed indicators provide valuable tools to monitor MAR projects, assess their effectiveness, and assist decision-makers in promoting sustainable water management practices. By integrating these indicators and methodologies into decision-making processes, stakeholders can make informed choices that enhance water availability, address hydric stress, and ensure the long-term sustainability of water resources.

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Acknowledgement

The AGREEMAR project is funded by National Funding Agencies from: Germany (Bundesministerium für Bildung und Forschung – BMBF, grant no. 02WPM1649), Cyprus (Research & Innovation Foundation – RIF, grant no. 0321-0024), Portugal (Fundação para a Ciência e a Tecnologia – FCT, grant no. PRIMA/0004/2021), Spain (Agencia Estatal de Investigación, Ministerio de Ciencia e Innovación – MCI, grant no. PCI2022-133001) and Tunisia (Ministère de l'Enseignement Supérieur et de la Recherche Scientifique – MESRSI, grant no. PRIMA/TN/21/07). The project is funded under the Partnership for Research and Innovation in the Mediterranean Area (PRIMA). The PRIMA Programme is supported under Horizon 2020 by the European Union's Framework for Research and Innovation.

Annex.

Indicators for sustainable water resources management

1. Environmental indicators:

1.1. ENV1: Urban Water Supply Sustainability (SHU)

$$SHU = (Reliability * Resilience * (1 - vulnerability))^{1/3}$$

Reliability is calculated as follows:

$$Reliability = \frac{Nº\ total\ months\ -\ nº\ failures}{Nº\ total\ months}$$

Where nº months represents the number of months of the simulation period of the management model. While nº failures are the months in which the urban demand has had a deficit. The deficit being the difference between demand and supply.

Vulnerability is estimated as follows:

$$V = \frac{\sum_{t=1}^{º failures} \frac{Def_t}{Dem_t}}{nº\ failures}$$

As can be seen, vulnerability is calculated as the average of the deficit (or failure) percentage. The deficit percentage is calculated as the quotient between the deficit (def_t) and the demand for that month (Dem_t). All ratios are summed and divided by the number of months with failure (num failures).

Finally, the resilience is calculated as:

$$R_s = \frac{\sum(nº\ times_t\ No\ failure\ \rightarrow fallo_{\ t+1} = 1)}{nº\ failures}$$

The numerator is based on estimating the number of months in which there is no failure but the following month there is a failure. The denominator is the number of months with failure. Resilience gives the probability of entering a failure streak with respect to total failures.

<u>Calculation method for aggregation:</u>

The indicator is calculated individually for each urban demand unit (UDU) in the basin. First, an aggregation is made at the subsystem scale by means of a weighted average of the indicator for each unit, the weighting weight being the annual demand.

$$I_s = \sum_{i}^{n} w_i * I_i$$

Where I_s is the subsystem indicator, I_i is the indicator for UDU "i" and w_i is the annual demand of UDU "i". The number of UDUs is n.

The final indicator for the river basin district is obtained in the same way.

1.2. ENV2: Hydrological Alteration indicator (IAH)

<u>IAH1 : index of magnitude of annual inflows</u>

The IAH1 is obtained by calculating the quotient between the average of the annual contributions in altered regime $\overline{Q_{AA}}$ and natural $\overline{Q_{AN}}$. A value is determined for each year, the indicator being the average of the value obtained for each year.

$$IAH1 = \frac{\overline{Q_{AA}}}{\overline{Q_{AN}}}$$

<u>IAH2: Index of the magnitude of monthly inflows</u>

The IAH2 is obtained by calculating the quotient between the average of the monthly contributions in altered regime $\overline{Q_{MA}}$ and natural $\overline{Q_{MN}}$. A value is determined for each month, the indicator being the average of the 12 months.

$$IAH2 = \frac{\overline{Q_{MA}}}{\overline{Q_{MN}}}$$

IAH3: Index of usual variability

The IAH3 is obtained by calculating the quotient of the difference between the values of the 10th and 90th percentiles of the time series on a monthly scale, for the altered regime and the natural regime.

$$IAH3 = \frac{(Q_{10} - Q_{90})_{ALTERED}}{(Q_{10} - Q_{90})_{NATURAL}}$$

Where: $Q10$ is the 10th percentile of the inputs in altered or natural regime; $Q90$ is the 90th percentile of the inputs in altered or natural regime.

IAH4: Index of extreme Variability

The IAH4 is obtained by calculating the quotient of the difference between the maximum and minimum monthly inflows, for altered and natural regimes.

$$IAH4 = \frac{(Q_{maxT} - Q_{minT})_{ALTERED}}{(Q_{maxT} - Q_{minT})_{NATURAL}}$$

Where: Q_{maxT} is the maximum monthly contribution of the time series; Q_{minT} the minimum monthly contribution of the time series.

IAH5: Index of Seasonality of Maximums

The IAH5 is obtained by calculating the offset that exists between the month of maximum contribution for each year of the series between the altered regime and the natural regime, being 6 the maximum possible offset. Once the offset has been determined, the average offset will be obtained.

$$IAH5 = 1 - \frac{\overline{Off}_{max}}{6}$$

Where: $\overline{Off}_{max}$ Average offset of the series between maximum monthly values.

IAH6. Index of Seasonality of minimums

The IAH6 is obtained by calculating the offset that exists, for each year of the flow series, from the month of minimum inflow between the altered regime and the natural regime, with 6 being the maximum possible offset. Once the offset has been determined, the average offset will be obtained.

$$IAH6 = 1 - \frac{\overline{Des}_{min}}{6}$$

Where: $\overline{Off}_{min}$ Average offset of the series between minimum monthly values.

IAH7: Index of magnitude of the usual floods

The IAH7 is obtained by calculating the ratio of the usual flood flows (which is set at the 5th percentile, according to IAHRIS methodology) in the altered and natural regimes. The classified flow curve is constructed from the monthly average flow data for the entire period.

$$IAH7 = \frac{(Q_5)_{ALTERED}}{(Q_5)_{NATURAL}}$$

Where: $Q5$ is the 5th percentile of the inputs in altered or natural regime.

IAH8: Index of Variability of the usual floods

The IAH8 is obtained by calculating the quotient of the coefficients of variation $Cv5$ in altered regime and in natural regime. The coefficient of variation is defined from the series of flood flows that are higher than the 5th percentile (Q>$Q5$).

$$IAH8 = \frac{(Cv_5)_{ALTERED}}{(Cv_5)_{NATURAL}}$$

Where: $Cv5$ is the coefficient of variation (μ/σ) of the series of flood flows greater than $Q5$; μ is the mean and σ is the standard deviation.

IAH9: Index of Seasonality of Floods

The IAH9 is obtained by first determining the number of years that the mean monthly flow exceeds the usual flood flow defined by $Q5$, both for the altered regime and the natural regime for each month. Subsequently, the monthly index is calculated from the difference between both values, establishing that, if this exceeds the value of 5, the index is 0. Finally, the total index corresponds to the average of the 12 monthly values.

$$IAH8 = \frac{1}{12}\sum_{m=1}^{12} Max\left(0;\ \frac{5-|(i_{\mathrm{NAT}},m-i_{\mathrm{ALT}},m)|}{5}\right)$$

Where: m is the month of the year; i_{NAT} number of years in which the monthly mean flow $\overline{Q_{MN}}$ of the month "m" is higher than the usual flood flow $Q5$, in natural regime; i_{ALT} number of years in which the mean monthly flow $\overline{Q_{MA}}$ of month "m" is higher than the usual flood flow $Q5$, in altered regime.

IAH10: Index of Magnitude of usual droughts

The IAH10 is obtained by calculating the quotient of the usual drought flows (which is set at the 95th percentile, according to IAHRIS methodology) in altered and natural regimes. The classified flow curve is constructed from the average monthly flow data for the entire period.

$$IAH10 = \frac{(Q_{95})_{ALTERED}}{(Q_{95})_{NATURAL}}$$

Where: $Q95$ is 95th percentile of inputs in altered or natural regime.

IAH11: Index of Variability of usual droughts

The IAH11 is obtained by calculating the quotient of the coefficients of variation $Cv95$ in altered regime and natural regime. The coefficient of variation is defined from the series of flood flows that are greater than the 95th percentile (Q>$Q95$).

$$IAH11 = \frac{(Cv_{95})_{ALTERED}}{(Cv_{95})_{NATURAL}}$$

Where: $Cv95$ is the coefficient of variation (μ/σ) of the series of flood flows greater than $Q95$. μ is the mean and σ is the standard deviation.

IAH12. Index of Seasonality of droughts

The IAH12 is obtained by first determining, for each month of the year, the number of years that the mean monthly flow exceeds the usual drought flow defined by $Q95$, both for the altered regime and the natural regime for each month. Subsequently, the monthly index is calculated from the difference between both values, establishing that, if this exceeds the value of 5, the index is 0. Finally, the total index corresponds to the average of the 12 monthly values.

$$IAH12 = \frac{1}{12}\sum_{m=1}^{12} Max\left(0;\ \frac{5-|(i_{\mathrm{droNAT}},m-i_{\mathrm{seqALT}},m)|}{5}\right)$$

Where:

m month of the year; i_{NAT} number of years in which the mean monthly flow $\overline{Q_{MN}}$ of month "m" is higher than the usual drought flow $Q95$, in natural regime; i_{ALT} number of years in which the mean monthly flow $\overline{Q_{MA}}$ of month "m" is higher than the usual drought flow $Q95$, in altered regime.

IAHG: Index of Global Hydrological Alteration

It can be considered as the index that synthesizes and characterizes a body of water from the point of view of the alteration of the natural flow regime since it takes into account the different aspects analyzed by the previous indexes and that directly affect the system. It is obtained by calculating the average of the twelve indices described above:

$$IAH = \frac{1}{12}\sum_{i=1}^{12} IAH_i$$

Where: i is the index number and IAH_i is the hydrologic alteration index i.

Calculation method for aggregation:

Once the indices have been calculated for each tranche under study, they are aggregated at the subsystem level or at the demarcation level using the weighted average of the overall index.

$$I_s = \sum_{i}^{n} w_i * I_i$$

Where I_s is the subsystem indicator, I_i is the indicator for the section "i" and w_i is the contribution of subsystem "i". Where n is the number of subsystems to be added.

The final indicator for the river basin district is obtained in the same way.

1.3. ENV3: Agricultural Water Sustainability (SHA)

$$SHA = (Reliability * Resilience * (1 - vulnerability))^{1/3}$$

Reliability is calculated as follows:

$$Reliability = \frac{N^{\underline{o}}\, total\ months\ -\ n^{\underline{o}}\, failures}{N^{\underline{o}}\, total\ months}$$

Where nº months represents the number of months of the simulation period of the management model. While nº failures are the months in which the urban demand has had a deficit. The deficit being the difference between demand and supply.

Vulnerability is estimated as follows:

$$V = \frac{\sum_{t=1}^{^{o}failures} \frac{Def_t}{Dem_t}}{n^{\underline{o}}\, failures}$$

As can be seen, vulnerability is calculated as the average of the deficit (or failure) percentage. The deficit percentage is calculated as the quotient between the deficit (def_t) and the demand for that month (Dem_t). All ratios are summed and divided by the number of months with failure (num failures).

Finally, the resilience is calculated as:

$$R_s = \frac{\sum(n^{\underline{o}}\, times_t\ No\ failure\ \rightarrow fallo_{\ t+1} = 1)}{n^{\underline{o}}\, failures}$$

The numerator is based on estimating the number of months in which there is no failure but the following month there is a failure. The denominator is the number of months with failure. Resilience gives the probability of entering a failure streak with respect to total failures.

Calculation method for aggregation:

The indicator is calculated individually for each agriculture demand unit (aDU) in the basin. First, an aggregation is made at the subsystem scale by means of a weighted average of the indicator for each unit, the weighting weight being the annual demand.

$$I_s = \sum_{i}^{n} w_i * I_i$$

Where I_s is the subsystem indicator, I_i is the indicator for ADU "i" and w_i is the annual demand of UDU "i". The number of ADUs is n.

The final indicator for the river basin district is obtained in the same way.

2. Socio-economic indicators:

2.1. ECON1: Average apparent water productivity in the primary sector

Data needed for its calculation: For the calculation of this indicator, it is necessary to have the total gross value added (GVA) of the primary sector from Eurostat and the virtual water used in each of the economic sectors included in the primary sector (data on water used in agriculture, livestock and forestry). The water used in agriculture is obtained from the hydrological models, considering the effective rainwater and irrigation water used by the plant for its optimal development. In the case of rainfed crops, only the effective rainfall will be considered, while in irrigated crops both concepts and quantities will be considered. Water data for pasture are also provided by the models, while data on the amount of water used by livestock and forestry are obtained from the official statistics of each country in the SUDOE territory.

$$rimary\ sector\ productivity = \frac{GVA\ primary\ sectoro}{m3\ of\ water\ in\ primary\ sector}$$

Unit: €/m^3

2.2. ECON2: Average apparent water productivity in agriculture

Data needed to calculate this indicator: To calculate this indicator, it is necessary to have the economic value of the production of the agricultural sector from the basin management agencies and the direct water used in agriculture. The water used in agriculture is obtained from the hydrological models, considering the effective rainwater and irrigation water used by the plant for its optimal development. In the case of rainfed crops, only the effective rainfall will be considered, while in the case of irrigated crops, both concepts and quantities will be considered.

$$Agricultural\ sector\ productivity = \frac{Economic\ value\ of\ agricultural\ production}{m^3\ of\ water\ in\ the\ agricultural\ sector}$$

Unit: €/m^3

2.2.1. ECON2a: Average apparent productivity of irrigation water in agriculture

Data needed to calculate this indicator: To calculate this indicator, it is necessary to have the economic value of the production of the agricultural sector from the basin management agencies and the direct water used in agriculture. The water used in agriculture is obtained from the hydrological models, considering the effective rainwater and irrigation water used by the plant for its optimal development. In the case of rainfed crops, only the effective rainfall will be considered, while in the case of irrigated crops, both concepts and quantities will be considered.

$$Irrigation\ water\ productivity\ in\ agricultural\ sector = \frac{Economic\ value\ of\ agricultural\ production}{m^3\ of\ water\ in\ the\ agricultural\ sector}$$

Unit: €/m^3

2.2.2. ECON2b: Average apparent water productivity in irrigated agriculture

Data needed to calculate this indicator: To calculate this indicator, it is necessary to have the economic value of the production of the agricultural sector from the basin management agencies and the direct water used in agriculture. The water used in agriculture is obtained from the hydrological models, considering the effective rainwater and irrigation water used by the plant for its optimal development. In the case of rainfed crops, only the effective rainfall will be considered, while in the case of irrigated crops, both concepts and quantities will be considered.

$$Water\ productivity\ in\ irrigated\ agriculture = \frac{Economic\ value\ of\ irrigated\ production}{m^3\ of\ irrigation\ water + effective\ irrigation\ rainfall}$$

Unit: €/m^3

2.2.3. ECON2c: Average apparent productivity of irrigation water in irrigated agriculture

Data needed to calculate this indicator: To calculate this indicator, it is necessary to have the economic value of irrigated agriculture production from the basin management agencies and the direct water used in agriculture. The water used in agriculture is obtained from the hydrological models, considering the effective rainwater and irrigation water used by the plant for its optimal development. In the case of rainfed crops, only the effective rainfall will be considered, while in the case of irrigated crops, both concepts and quantities will be considered.

$$Irrigation\ water\ productivity\ in\ irrigated\ agriculture = \frac{Economic\ value\ of\ irrigated\ agriculture\ production}{m^3\ of\ irrigation\ water\ in\ irrigated\ agriculture}$$

Unit: €/m^3

2.2.4. ECON2d: Average apparent water productivity in rainfed agriculture

Data needed to calculate this indicator: To calculate this indicator, it is necessary to have the economic value of the production of the agricultural sector from the basin management agencies and the direct water used in agriculture. The water used in agriculture is obtained from the hydrological models, considering the effective rainwater and irrigation water used by the plant for its optimal development. In the case of rainfed crops, only the effective rainfall will be considered, while in the case of irrigated crops, both concepts and quantities will be considered.

$$Rainfed\ agricultural\ water\ productivity = \frac{Economic\ value\ of\ rainfed\ agricultural\ production}{m^3\ of\ effective\ rainfall}$$

Unit: €/m^3

2.3. ECON3: Average apparent water productivity in the secondary sector ECON4: Water productivity in the tertiary sector

Data required for its calculation: For the calculation of this indicator, it is necessary to have the total GVA of the secondary sector from Eurostat and the virtual water used in each of the economic sectors included in them. The data on water in the industrial and construction sectors were obtained from the official statistics of each country in the SUDOE territory.

$$Secondary\ sector\ productivity = \frac{GVA\ secondary\ sector}{m^3\ of\ water\ in\ the\ secondary\ sector}$$

Unit: €/m^3

2.4. ECON4: Average apparent water productivity in the tertiary sector

Data needed for its calculation: For the calculation of this indicator, it is necessary to have the total GVA of the tertiary sector and the virtual water used in it, as well as an estimate of the water used for human consumption. The data for water in the service sector and for human consumption were obtained from the official statistics of each country in the SUDOE territory.

$$Tertiary\ sector\ productivity = \frac{GVA\ tertiary\ sector}{m^3\ of\ water\ in\ tertiary\ sector + human\ consumption}$$

Unit: €/m^3

2.5. ECON5: Water use intensity per employee in the primary sector

Data needed to calculate this indicator: To calculate this indicator, it is necessary to have the number of hours worked by employees in the primary sector and the virtual water used in each of the economic sectors included in the primary sector. The water used in agriculture is obtained from the hydrological models, considering the effective rainwater and irrigation water used by the plant for its optimal development. In the case of rainfed crops, only the effective rainfall will be considered, while in the case of irrigated crops, both concepts and quantities will be considered. Water data for pasture are also provided by the models, while data on the amount of water used by livestock and forestry are obtained from the official statistics of each country in the SUDOE territory.

Water intensity per employee in the primary sector is calculated based on:

$$= \frac{m^3\ of\ water\ in\ the\ primary\ sector}{nº\ of\ full - time\ equivalent\ employees}$$

$$= \frac{m^3\ of\ water\ in\ the\ primary\ sector}{n°\ of\ hours\ worked\ in\ the\ primary\ sector / nº\ average\ hours\ per\ year\ per\ full - time\ employee}$$

Unit: m3/person full time equivalent employee

2.6. ECON6: Water use intensity per employee in the secondary sector

Data needed to calculate this indicator: To calculate this indicator it is necessary to have the number of hours worked by employed persons in the secondary sector available in Eurostat and the virtual water used in each of the economic sectors included in them. The data on water in the industrial and construction sectors were obtained from the official statistics of each country in the SUDOE territory.

Water intensity per employee in the secondary sector is calculated based on:

$$= \frac{m^3 \ of \ secondary \ sector \ water}{nº \ of \ full - time \ equivalent \ employees}$$

$$= \frac{m^3 \ of \ secondary \ sector \ water}{nº \ of \ hours \ worked \ in \ the \ secondary \ sector / nº \ average \ hours \ per \ year \ per \ full - time \ employee}$$

Unit: m^3/person full time equivalent employee

2.7. ECON7: Water use intensity per employee in the tertiary sector

Data needed to calculate this indicator: To calculate this indicator, it is necessary to have the number of hours worked by employed persons in the tertiary sectors available in Eurostat and the virtual water used in each of the economic sectors included in them. The data on water in the service sector and human consumption were obtained from the official statistics of each country in the SUDOE territory.

Water intensity per employee in the tertiary sector is calculated based on:

$$= \frac{m^3 \ of \ tertiary \ sector \ water + human \ consumption}{nº \ of \ full - time \ equivalent \ employees}$$

$$= \frac{m^3 \ of \ tertiary \ sector \ water + human \ consumption}{nº \ of \ hours \ worked \ in \ the \ tertiary \frac{sector}{n} º \ average \ hours \ per \ year \ per \ full - time \ employee}$$

Unit: m^3/person full time equivalent employee

3. Governance indicators:

3.1. GOB1: Decline of governance tools at the local level

Data needed to calculate this indicator: Information available in planning documents of each river basin district.

The indicator is calculated as a weighted average of the variables by the number of modalities that take these variables, then by the number of variables taken into account.

$$Local \ decay = \left(\left(\frac{TerrDispo}{2} \right) + \left(\frac{ReunionTerr}{2} \right) + \left(\frac{AppliTer}{2} \right) \right) /3$$

TerrDispo: Existence of activities in the entire territory of the demarcation: I point (absence) or 2 points (presence).

TerrMeeting: Existence of exclusively territorial sessions: variable indicating whether territorial meetings have been held: I point (no meeting) or 2 points (meeting).

AppliTerr: Indicates the existence of territorial delimitations within the basin with the objective of repeating the participation schemes in each of the territories: I point (no delimitations exist) or 2 points (delimitations exist).

3.2. GOB2: Degree of transparency

Data needed to calculate this indicator: Information available in the planning documents in each river basin.

The indicator is calculated on a weighted average of the variables by the number of modalities that take these variables, then by the number of variables taken into account.

$$Degree \ of \ transparency = \left(\left(\frac{DiffAutre}{2} \right) + \left(\frac{Diffpresse}{2} \right) + \left(\frac{DispoDoc}{2} \right) \right) /3$$

DiffAutre: Indicates the existence of means other than the press to communicate the opening of the consultation to the general public. The variable takes two forms: I point in case of lack of implemented means, or 2 points in case of actually deployed means.

Diffpresse/ Indicates the dissemination through various media (other than the official bulletin) of the opening of the consultation period. The variable takes two forms: I point in the case where no other means of dissemination than the official gazette has been used, and 2 points in the case where other means of dissemination have been used. Two forms: 1 or 2 points

DispoDoc: Effort made by the organization to make available the documents sent for consultation (Plan/SDAGE), taking into account the medium used. The variable takes four modalities according to the degree of effort deployed: 1 point if it is non-existent, 2 points if it is weak, 3 points if this effort is medium, or 4 points if this effort is important.

3.3. GOB3: Participation in planning

Data needed to calculate this indicator: The information is available in the planning documents of each river basin district.

The indicator is calculated on a weighted average of the variables by the number of modes taking these variables, then by the number of variables considered.

$$Planning\ participation = \left(\left(\frac{DPADI}{4}\right) + \left(\frac{DPAQI}{4}\right)\right)/3$$

DPADI: Number of active participation mechanisms used for the drafting of documents intended for public consultation. This variable is constructed from 3 classes: non-existent, low or important (1, 2 or 3).

DPAQI: Number of active participation instruments when writing the summary of important issues. The number of instruments deployed for each watershed has been organized into 4 classes corresponding to four categories: I point when there is no device, 2 points when this number is low, 3 points when it is medium or 4 when it is important.

3.4. GOB4: Type of participation

Data needed to calculate this indicator: Information available in the planning documents of each river basin district.

The indicator is calculated on a weighted average of the variables by the number of modalities that take these variables, then by the number of variables considered.

$$Participation\ = \left(\left(\frac{Approchepublic}{3}\right) + \left(\frac{Parcticipation\ souhaite}{3}\right) + \left(\frac{Diversite}{3}\right) + \left(\frac{Cible}{2}\right)\right)/4$$

Approchepublic: indicates the type of approach adopted by the managers during the concertation phase, taking into account the sectors involved. This variable is divided into three categories: 1 point when there is no concertation, 2 points when only one sector is present at a time, or 3 points when concertation is multisectoral.

Participation souhaite: describes the type of exchange at the participation meetings. The variable is composed of three modalities according to the type of participation that takes place: 1 point when it is an informative meeting, 2 points when it is a matter of collecting stakeholders' opinions, or 3 points when participation leads to real exchanges (dialogic participation).

Diversite: diversity of participation schemes during public consultation. The variable is composed of three modes, according to the more or less strong heterogeneity of the instruments deployed in each basin: I point when this diversity is weak, 2 points when it is average or 3 points when it is high.

Cible: Indicates the type of public addressed by the organization during the whole process of participation in the development of the hydrological plan. The variable comprises two modalities: I point when the participation concerns a restricted public, or 2 points when the participation concerns the general public.