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BLUE RECHARGE

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Handbook: Results of the case studies

TABLE OF CONTENTS

1 Introduction

This document is developed as deliverable of the Action 2.3 of the Workpackage 2 *Integrated case studies*. It has the scope of giving some operative indications for the implementation of MAR (Managed Aquifer Recharge) projects aimed at the valorisation of the environmental benefits through the Blue Credits mechanism designed in the BLUE RECHARGE project.

The handbook will face five arguments and the related issues to deal with for a successful implementation and valorisation of a MAR project:

- Definition of the MAR objectives
- Principles for a selection of a MAR
- Involvement of the actors
- Quantification of the MAR benefits and monitoring activities
- Blue credits mechanism feasibility

Each chapter contains indications about the topic and examples of operative solutions adopted in the case studies.

In the BLUE RECHARGE project two pilot activities have been carried out in Istria and Emilia-Romagna regions. In both pilot areas MAR techniques are implemented:

- a wetland in agricultural land in Emilia-Romagna
- a treated wastewater subsurface discharge in Istria

In Emilia-Romagna the pilot site is located in the Po river Delta area and the activity is aimed to model and estimate the efficacy of the MAR in terms of aquifer recharge and sea salt intrusion mitigation. From a hydrogeological point of view, the site is located on a river terrace characterized by permeable granular material, and the aquifer is of the phreatic type.

In Istria the pilot site is located in the southern part of the region and presents groundwater critical conditions in terms of quantity and quality. The aquifer is a karstic one. The activity is focused on investigating the optimisation of wastewater treatment processes and assessing the feasibility of subsurface disposal techniques in terms of recharge potential, groundwater quality (e.g. salinisation, nitrates) and risk assessment.

The case studies are different for context, type of aquifer and adopted techniques. In the final chapter a comparison of differences and similarities about the way of handling the analyzed topics in the pilot regions is elaborated.

2 Definition of the MAR objectives

The creation of a MAR makes possible to achieve a wide range of objectives, aimed at being valorized through blue credits, ranging from guaranteeing water supply and security, to preserving and increasing water quality, to generating environmental and climate benefits, to contributing to the management of flood and storm up to producing economic benefits.

A portfolio of potential objectives is described with the aim to highlights the versatility of the MAR techniques.

- **Water supply and security**

  The objective of the MAR can refer either to support the long-term stability of water supplies or serve as a back-up during periods of drought. The specific objectives of the MAR can therefore be:

  - **Depleted aquifers preservation:** MAR can be realized in order to rise groundwater levels to sustainable levels in over-extracted aquifers.
  - **Storage increase:** MAR allows to store water underground for use during dry seasons or droughts, increasing reliability and long-term water security.

- **Water quality improvement**

  MAR can be designed in order to exploit the natural capacity of aquifers to filter water, removing contaminants and improving overall groundwater quality. In addition, a careful design of the MAR, for example by creating a wetland, can make it possible to exploit the self-purifying effect of aquatic plants and of the entire wetland, so as to introduce good quality water into polluted aquifers. The specific objectives of the MAR can therefore be:

  - **Natural contaminant filtration:** the MAR allows to take advantage of the soil and rock layers that act as a natural filter, removing pathogens, suspended solids, and some contaminants from the recharge water.
  - **Contamination reduction:** the introduction of good quality water through the MAR permit to dilute pollutants in the aquifer.

- **Environmental preservation and improvement**

  The implementation of a MAR can be aimed at obtaining environmental benefits, which can be the primary objective or a co-benefit that further increases its "value". Specific ecological objectives may relate to:

  - **Biodiversity preservation and improvement:** the creation of a MAR specifically designed for the protection of the ecosystem, for example through the creation of wetlands, allows to increase the presence of habitats and biodiversity and to promote ecological connectivity.

  - **Ecosystems support**: a MAR aimed at ensuring adequate water levels for rivers, wetlands and other groundwater-dependent habitats prevents them from being damaged due to the lowering of groundwater levels.
  - **Saltwater intrusion mitigation**: a relevant issue related to aquifer dynamics is saltwater intrusion, i.e., the encroachment of seawater into coastal surface and groundwater bodies. This phenomenon is exacerbated by overexploitation of groundwater resources and sea-level rise, both of which are linked to climate change. In coastal areas, therefore, the MAR can be implemented with the aim of pushes back saltwater, protecting freshwater aquifers and preventing saltwater intrusion from making large areas unproductive and from reducing drastically natural habitats.
  - **Prevents Land Subsidence**: a MAR by replenish aquifers may prevents ground from sinking due to over-extraction.
- **Flood & stormwater management**: a specifically designed MAR may have the ability to capture excess stormwater and reducing runoff and flood risk.
- **Economic gain**: the possibility to generate revenue for the owner of the system to be reinvested in the development of MAR projects is at the base of the creation of the blue credits mechanism. It represents an option that can improve the business model of the MAR developer and support the diffusion of MAR techniques implementation.

The multiple functions performed by a MAR technique permits to design a MAR project able to pursue multiple objectives and valorise them also in terms of attractiveness, because projects that generate co-benefits are generally preferred by the buyers.

In the design phase of a MAR project is important to define the multiple objectives that could be addressed in order to analyse the real potential considering local context, MAR techniques feasibility and involvement of key stakeholders for the exploitation of results.

CASE STUDY ISTRIA

The selection of southern Istria for this case study is based on two important observations:

- it is one of only two groundwater bodies in Croatia that are currently categorised as having poor chemical status under the Water Framework Directive (WFD)
- the region is at risk of failing to achieve good quantitative status, particularly under the influence of increasingly frequent hydrological extremes such as droughts

Groundwater abstraction in the region has a long history and recent drought events —2012 and 2022 — have demonstrated the continued vulnerability of the system.

Hydrogeological records show significant spatial and temporal fluctuations in groundwater levels and chloride concentrations, suggesting that the risk of salinisation could increase with prolonged water stress. At the same time, inadequate treatment of recharge water could exacerbate nitrate contamination, especially in areas with shallow unsaturated zones and intensive agricultural runoff.

Against this background, the southern part of Istria is a very suitable test area for an integrated assessment of the feasibility of MAR. It presents a representative combination of technical, climatic and institutional challenges that are also found in other Mediterranean and Karst regions, making the results of this case study valuable for wider application and policy learning. Potential objectives that can be achieved are:

- **Water supply and security.** In southern Istria there are depleted aquifers with potential for the quantitative shortages and qualitative challenges, so MAR will potentially rise groundwater levels to sustainable levels. It will increase the storage capacity for use during dry seasons or droughts, in this case for technical use and irrigation, to preserve the other water sources and increase reliability and long-term water security.
- **Environmental preservation and improvement.** Since area of the interest is near the sea MAR will prevent the encroachment of seawater into groundwater body. The objective of MAR is to push back saltwater, protecting freshwater aquifers and preventing saltwater intrusion, so that still can be used for irrigation. At the same time MAR may prevents some areas of ground from sinking due to over-extraction.

CASE STUDY EMILIA-ROMAGNA

The Italian case study was driven by concrete and well-known hydrogeological needs in the Mezzano Valley area. The area is characterized by a shallow phreatic aquifer, strongly influenced by fluctuations during periods of water scarcity. At the same time, issues of biodiversity losses in an highly intensive industrial and agricultural areas and structural risks of saltwater intrusion, exacerbated by subsidence processes and climate change pose further challenges for land planning and groundwater protection.

In this context, the main objective of the MAR was identified to favour the **preservation of a depleted aquifer**. Alongside this objective, the area aims at the **mitigation of groundwater salinization** processes while creating **viable habitats** for local and migratory bird species.

3 Principles for a selection of a MAR

The process of selecting a MAR scheme is a very crucial step in the overall design and implementation of MAR. Deciding which type of MAR to adopt and where to locate it requires a structured assessment and this assessment is not only important for all subsequent technical, operational and management steps, but it is also determinant for the functioning and robustness of the associated Blue Credits system.

Within the Blue Recharge project, a set of shared principles was followed to identify and design the two case studies. The Italian and Croatian case studies are therefore answers to a common set of guiding questions. Subsequently, the two cases diverge because of substantial differences in: territorial and environmental conditions, hydrogeological and geomorphological settings, local needs and pressures, and institutional, legal and governance frameworks.

According to EU guidance (e.g. *Guidance Document No. 39 – Common Implementation Strategy for the Water Framework Directive and the Floods Directive*), several MAR typologies are available. Moreover, within a given territory, multiple options usually exist for where a MAR scheme could be implemented. Thus, the selection process is inherently dual: it must jointly consider both the MAR typology and the specific location. It is important to note that the choice of MAR type and the choice of its physical location are strictly interlinked and mutually dependent; for this reason, they are treated together in the following sections.

This chapter explains the principles that guided the selection of MAR typologies and sites in the two project case studies.

These principles are presented and discussed in detail in the following subsections, and can be organized as follows:

1. Context analysis
2. Data availability and monitoring feasibility
3. Replicability

1 – Context Analysis

Context analysis is a fundamental component in the selection of both the MAR typology and the location where MAR will be implemented.

By context analysis it is meant the set of considerations that make a certain MAR type more or less suitable, and a certain area more or less appropriate for MAR implementation.

Within this principle, several dimensions were considered:

1. hydrogeological and soil characteristics,
2. environmental and socio-economic context,
3. aquifer behaviour,
4. expected benefits,
5. infrastructural context,
6. institutional and governance context.

Hydrogeological and Soil Analysis

The first step is the assessment of territorial characteristics, including the soil type and texture, the local hydrogeology (aquifer types, confinement, permeability, depth to groundwater, connectivity, etc.), and agronomic factors and land use.

Different hydrogeological conditions require different MAR approaches.

CASE STUDY ISTRIA

The selection of the site and the MAR typology was based on two main features: first, that there was a new waste water treatment plant (WWTP Loborika) started with operation, and treated waste water was discharged underground through infiltration field, and second, that there were already present several wells and drills that can be used as a control monitoring points.

Figure 1. WWTP Loborika

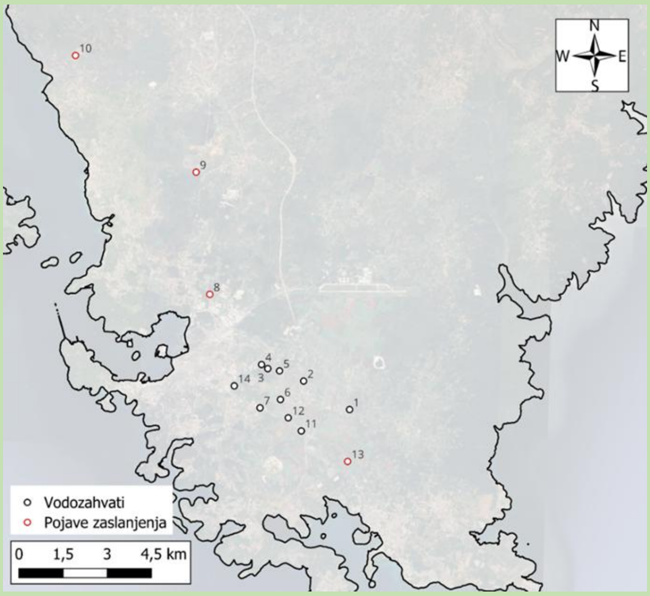


Figure 2. Presentation of the position of the existing wells of the Pula Waterworks (grey dots) with prominent localities where salinization phenomena have been recorded (red dots)

CASE STUDY EMILIA-ROMAGNA

In the Italian case study, the selection of the site and the MAR typology was carried out on the basis of rigorous technical criteria, aimed at ensuring the measurability of effects and the robustness of the assessments. The selected site was an existing agricultural wetland as it presented a combination of favourable hydrogeological, pedological and management conditions.

Figure 3. Wetland - Baldassari Farm

From a hydrogeological perspective, the presence of an unconfined aquifer at shallow depth, intercepted at approximately 130–135 cm below ground level, represented an essential requirement for MAR effectiveness. Pedological surveys highlighted silty and sandy-silty soils, compatible with diffuse infiltration processes, while in situ permeability tests made it possible to quantify saturated hydraulic conductivity in the different sectors of the wetland, revealing marked spatial heterogeneity.

Analysis of the Surrounding Environmental Context

The environmental analysis of the broader context allows the identification of:

- key drivers for MAR implementation (e.g. drought risk, salinization, water scarcity, ecological needs),

- existing or potential anthropogenic and natural pressures on groundwater and surface water (e.g. agriculture, urbanization, pollution sources).

Understanding the needs of the aquifer and of the area helps to select both the zone and the MAR type.

CASE STUDY ISTRIA

The map of the area of Southern Istria shows the locations of the wells included in the water supply system of the Pula Waterworks (blue) and the new wells in the hinterland of the Pula Airport (red) for the inclusion of which preparatory activities are being carried out. The lines are showing previously performed tracing testing and proven or suspected connections (pink, orange and red lines), or unproven connection (grey lines). The substantial data from previous monitoring programs could have been used to compare new data collected during the case study.

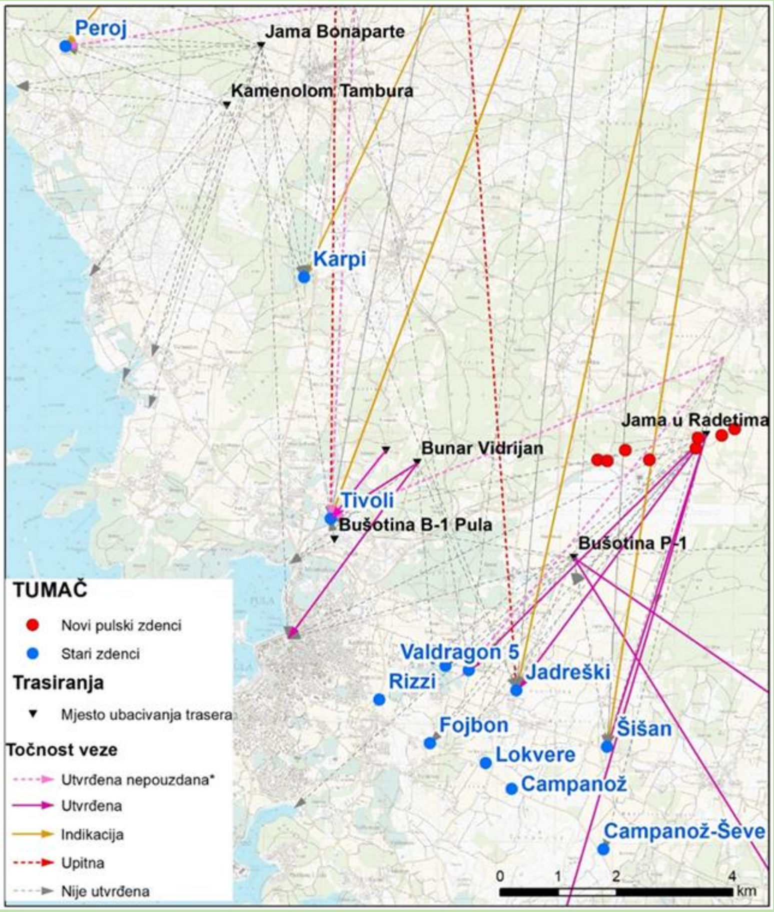


Figure 4. Positions of the wells and tested underground connections)

CASE STUDY EMILIA-ROMAGNA

In the context of the Italian case study, in Emilia-Romagna a sub-region wide assessment on soil and shallow watertable settings was performed to highlight the multi-purpose potential of MAR performed trough wet ecosystems. Here, as an example, public and private databases to deliver soil maps.

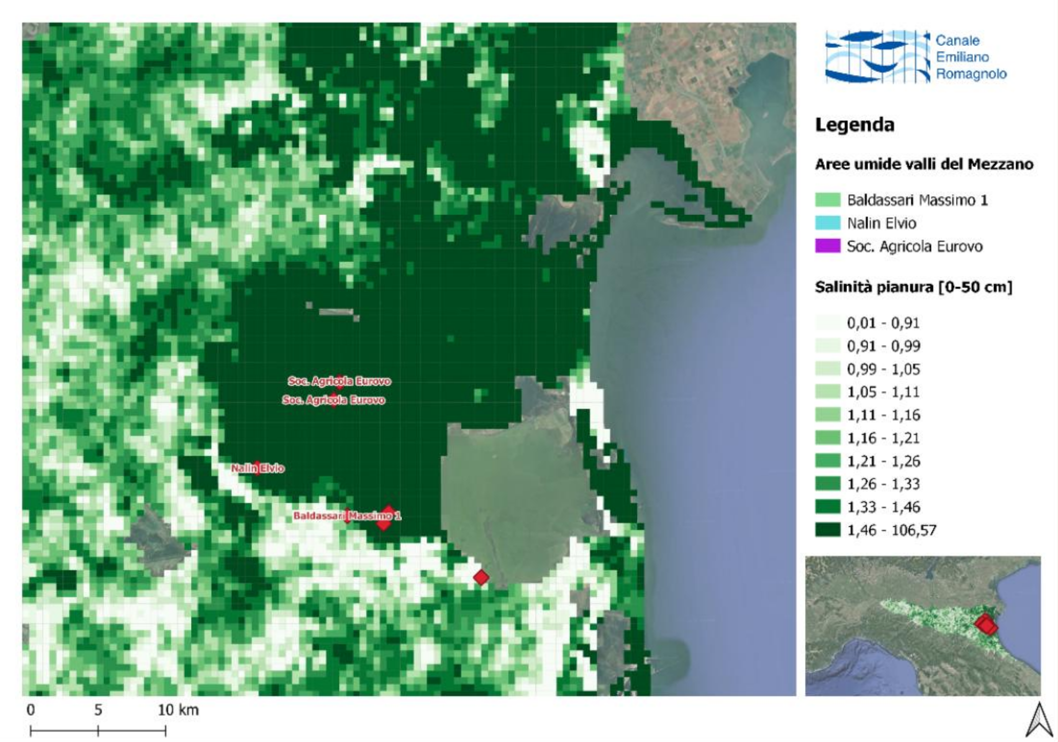


Figure 5. Salinity map of the Mezzano area (source: CER elaboration on public spatial databases of Regione Emilia-Romagna)

Aquifer Analysis and Behavior

The behavior of the target aquifer has been another key element. The area should be well characterized from a hydraulic point of view, with clear conceptual and numerical understanding of the aquifer, and the existence of an identifiable and direct correlation between recharge volumes (e.g. water stored in basins or injected through wells) and changes in groundwater levels (piezometric response). These aspects can influence where MAR is best located and how it is operated.

CASE STUDY ISTRIA

Monitoring groundwater levels and electrical conductivity was performed throughout the Case study period. Measuring devices (CTD Divers) for continuous monitoring of the level, temperature and electrical conductivity of water with hourly time discretization were installed on 5.3.2025 and were active until mid-January 2026. The devices were installed at 7 locations and at additional 3 locations periodic level measurements were carried out with a hand-held meter.

Location	**Jadreški**	**Tivoli**	**Karolina**	**Bušotina Loborika B-1**	**Bušotina BM 6/16**	**Bušotina BM 12/18**	**Karpi***	**Peroj***	**Škatari***
Water level (m n.m.)									
Av	5,90	1,48	0,88	31,5	24,2	19,9	6,0	0,85	9,65
Max	8,20	2,48	0,98	35,3	25,1	20,9	12,3	1,58	11,3
Min	4,13	0,78	0,80	30,2	23,2	19,1	2,3	0,58	8,87
Water temperature (°C)									
Av	14,5	13,8	14,6	13,6	14,0	14,0	13,9 **		
Max	14,6	14,1	14,8	15,5	14,1	14,2			
Min	14,5	13,1	14,4	13,6	14,0	14,0			
Conductivity (mS/cm)									
Av	0,884	0,844	0,839	0,942	0,833	0,564	0,843 **		
Max	0,948	0,889	0,901	0,992	0,861	0,621			
Min	0,844	0,767	0,792	0,424	0,752	0,223			

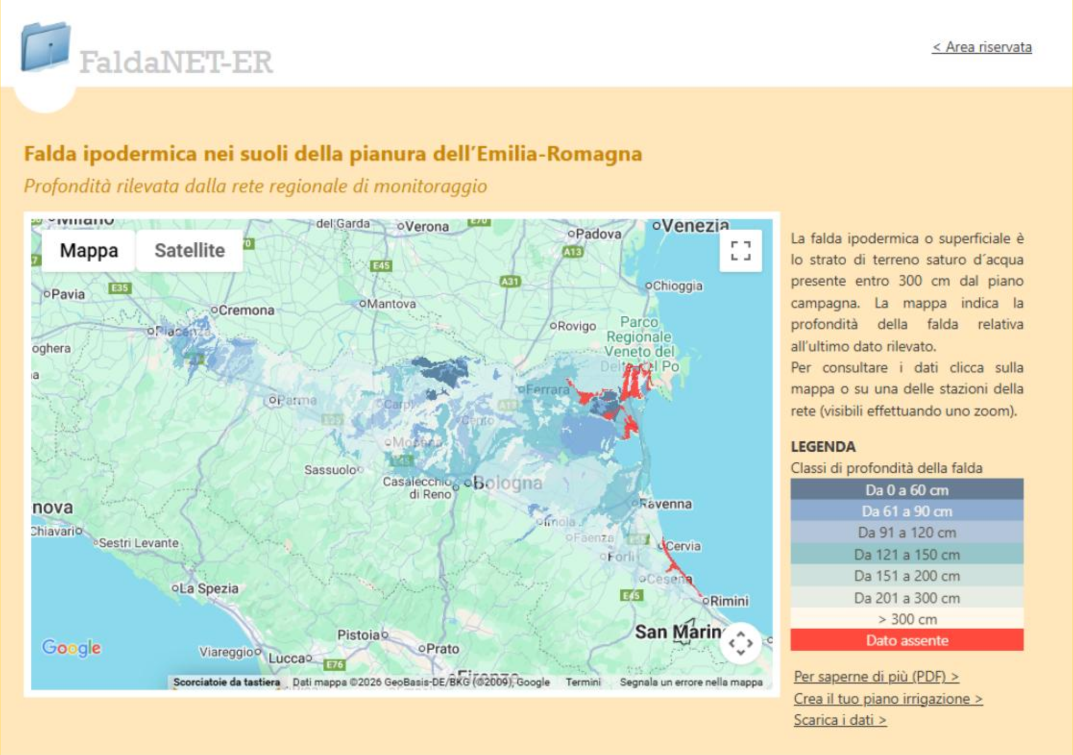
** Manually measured water levels*

*** Short measurement period (5/3/2025 - 7/5/2025), and only mean values are given*

Table 1 Mean, maximum and minimum values of water levels, temperature and electrical conductivity at all measured locations

CASE STUDY EMILIA-ROMAGNA

In the case of Emilia-Romagna, this aspect was addressed through the monitoring of groundwater levels and electrical conductivity at the regional scale. This is performed on a regularly basis by CER which in partnership with regional technical offices monitors shallow water table levels and quality in over 125 piezometers. Such data is made available within the FaldaNet platform (http://faldanet.consorziocer.it/Faldanet/retefalda/index) and allowed to select phreatics whose settings needed support from MAR initiatives both from the qualitative and quantitative perspectives.



Falda ipodermica nei suoli della pianura dell'Emilia-Romagna

Profondità rilevata dalla rete regionale di monitoraggio

La falda ipodermica o superficiale è lo strato di terreno saturo d´acqua presente entro 300 cm dal piano campagna. La mappa indica la profondità della falda relativa all'ultimo dato rilevato.
Per consultare i dati clicca sulla mappa o su una delle stazioni della rete (visibili effettuando uno zoom).

LEGENDA

Classi di profondità della falda

Da 0 a 60 cm
Da 61 a 90 cm
Da 91 a 120 cm
Da 121 a 150 cm
Da 151 a 200 cm
Da 201 a 300 cm
> 300 cm
Dato assente

Per saperne di più (PDF) >
Crea il tuo piano irrigazione >
Scarica i dati >

Figure 6. Homepage of the FaldaNet Platform

Benefit Analysis

Another key aspect considered in site selection is the maximization of benefits, both in terms of where groundwater recharge is particularly advantageous (e.g. areas with severe water scarcity, high salinity risk, strategic uses), and effectiveness of the recharge action (e.g. good infiltration capacity, strong hydraulic connectivity with the target aquifer, direct link to areas of demand).

Sites should be chosen where MAR can:

- deliver the maximum benefit compared to associated risks,
- act as a buffer against droughts and pollution,
- be close to the main needs (e.g. irrigation areas, drinking water sources, ecosystems).

CASE STUDY ISTRIA

Since the legislation for MAR is not yet defined in Croatia and especially apply of MAR with treated wastewater is not regulated, only Pilot test performance was possible, on limited area, and with limited influence on the underground aquifer. Water permit to conduct test was issued from Hrvatske vode, the control body for water sector in Croatia. Two new wells were drilled at the location of WWTP Loborika: application well, about 32 m deep and control well, about 100 m deep – first one to apply the tracer test agent, and second one to control the velocity of the flow and the residence time. At the same time with application of test agent monitoring was installed on additional 5 previously existing wells and springs that are located about 1,2 and 2,5 km southeast (2 wells), 5,7 km south (one well) and 4,3 and 6,1 km southwest (1 well and 1 spring respectively). These control points were chosen based on previously known information about water flow in underground aquifer.

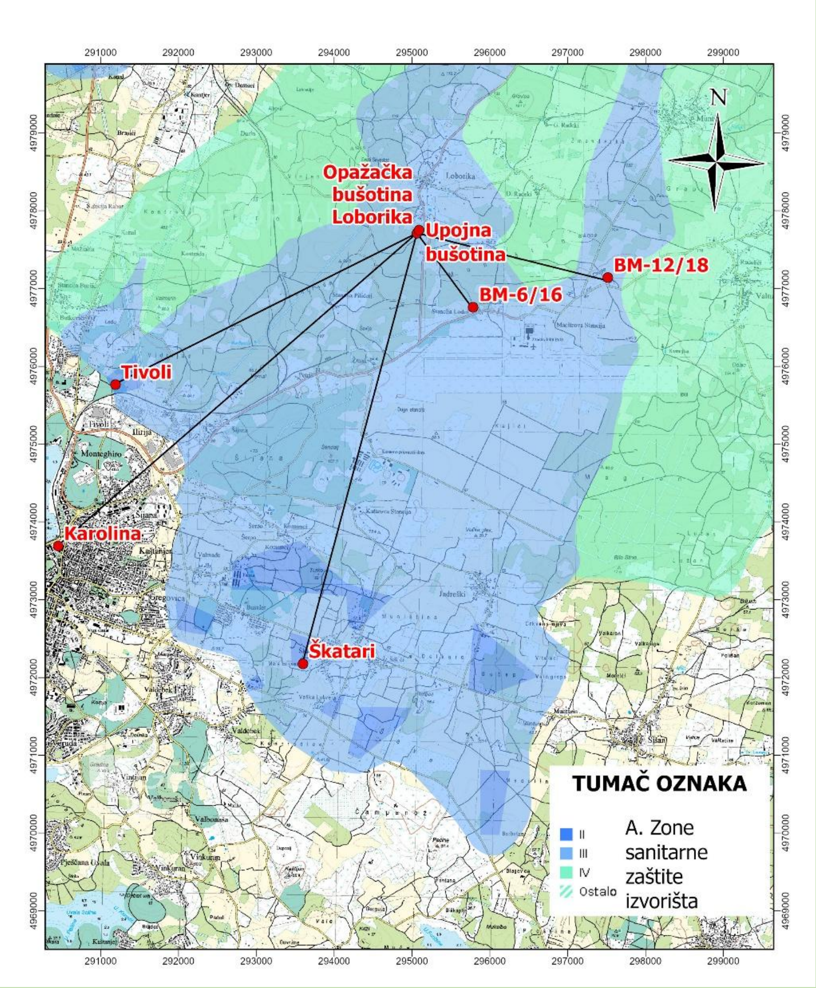


Figure 7. Map of locations included in the tracer test

CASE STUDY EMILIA-ROMAGNA

The selected MAR in Italy is characterized by a simple and well-controlled hydraulic system, consisting of three interconnected basins, supplied by pumping and equipped with overflow structures discharging into the reclamation canal. This configuration facilitated both operational management and the reconstruction of water balances, aimed at benefits estimations. This area is near to irrigation infrastructures hence provided with sustainable water sources.

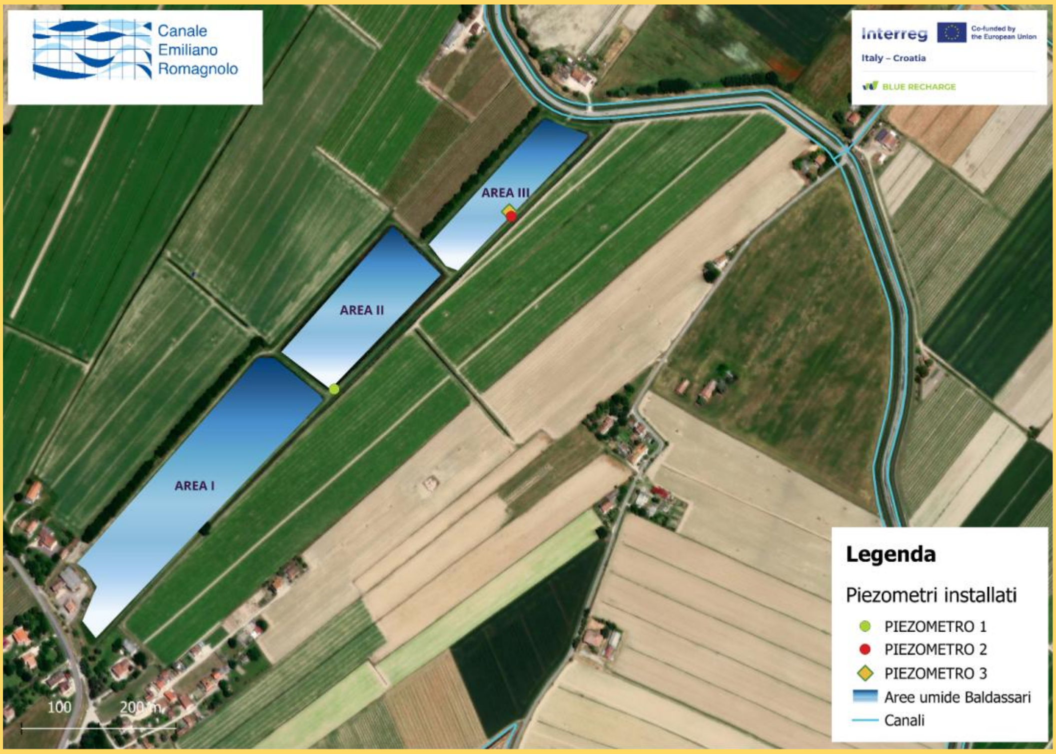


Figure 8. Wetland area of the Baldassari Farm, chosen as a case study for the Blue Recharge project.

Infrastructural Context

The presence (or absence) of pre-existing infrastructure was considered an important driver in selecting MAR locations.

Using existing infrastructure can reduce investment costs, simplify implementation, and facilitate monitoring and operation.

CASE STUDY ISTRIA

The infrastructure for water extraction and distribution in this area is present on all previously used wells and springs, since the process of capturing them started in the late 1800s, and the use for public water supply lasted until the early 2000s. Some of the wells were latter in use occasionally, and 3 of them are still in water supply system (Jadreški, Šišan and Ševe). On the sites, there are still pump stations and the water distribution pipes that can be easily repurposed for irrigation or other technical purposes.

Figure 9. Pumps at Spring Carolina in Pula and at well Tivoli

CASE STUDY EMILIA-ROMAGNA

Similarly to what has been performed in the analysis of the hydrogeological and soil settings, anthropogenic hydrological infrastructures have been taken into consideration to gain viable insights into the potential of water availability and allocation in the area aimed a implementing the MAR together with already existing wet ecosystems.

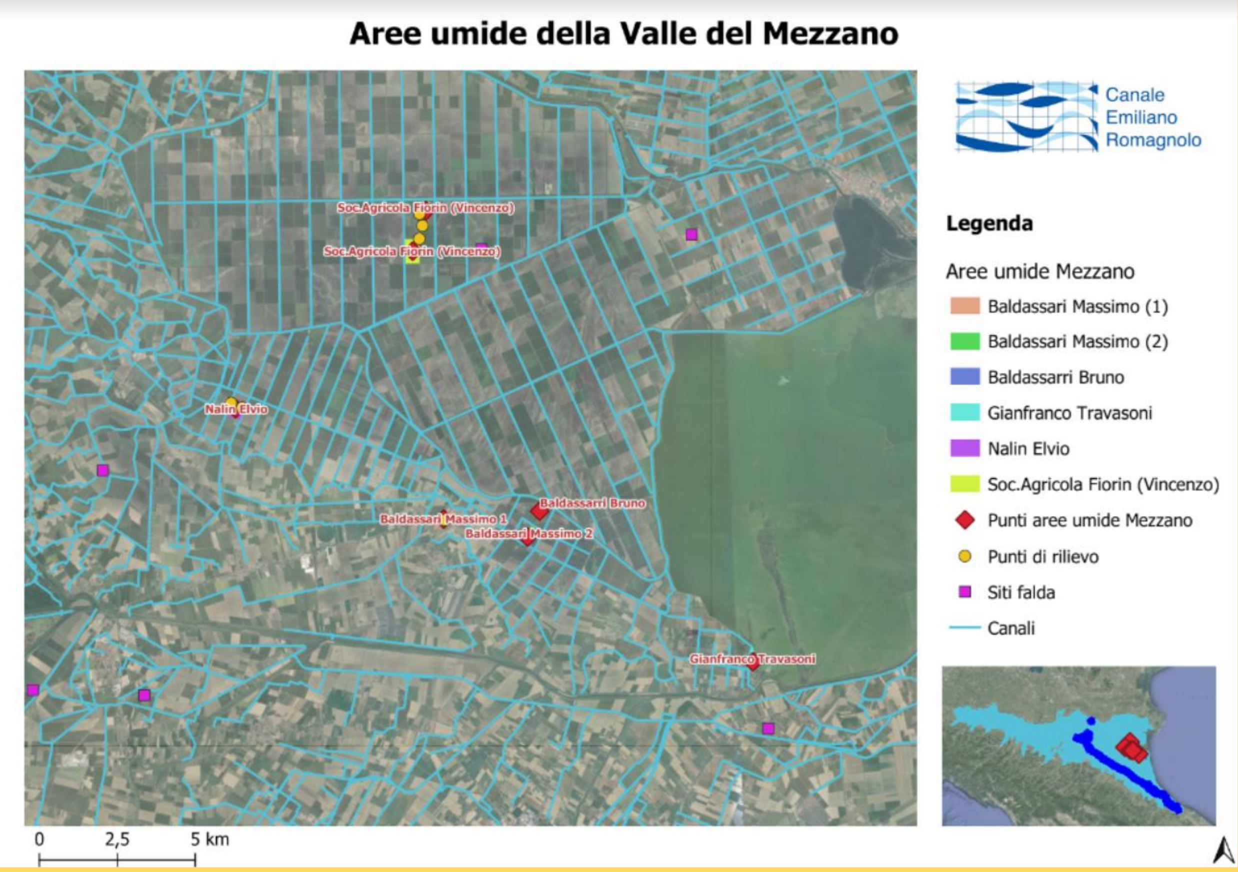


Figure 10.: Wetland areas in the Mezzano Valley

Institutional and Governance Context

Finally, the institutional and governance context was also evaluated as part of the context analysis, taking into account the different actors involved and their roles. A key criterion for selecting MAR sites is the willingness and engagement of stakeholders involved in implementation and operation (e.g. farmers, utilities, municipalities, water authorities).

CASE STUDY ISTRIA

According to new organization scheme for the water sector in Croatia there is one regional company that is responsible for water supply and sewage systems on the operational area, that is defined as water service provider in the service area. In case of Istria there are two regional companies territorially divided: on the south-east part of Istria water service provider is waterwork Vodovod Pula – Labin, on the north-west part is Istarski Vodovod. It is very convenient that the same company that is providing water supply is also responsible for water protection, especially in the water protection zones. In this way waterworks will have active role to preserve their own present and future water sources.

As a control and regulatory body for all issues related to water in the Republic of Croatia, there are Croatian Waters – Hrvatske vode. It is a legal entity for water management to protect life, health and property from the harmful effects of water, and to ensure the permanent availability of water by optimizing economic and environmental benefits on the principles of sustainable development. Croatian Waters closely cooperates with the competent ministry in the adoption of all water-related legislation. For any works and testing related to water and wastewater permits must be issued from Croatian waters.

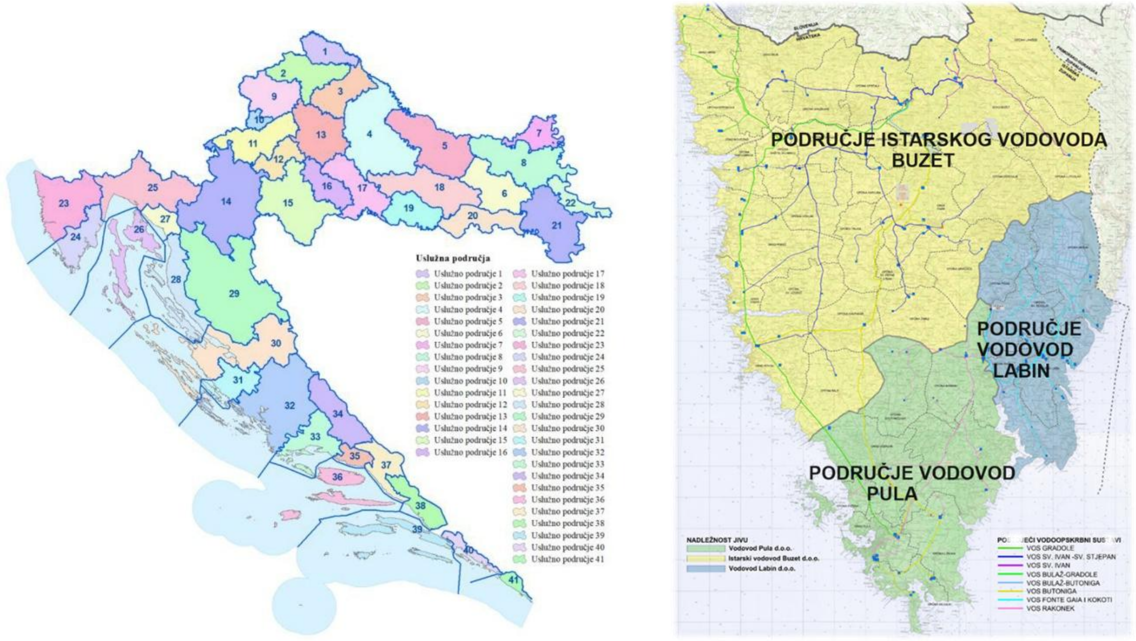


Figure 11. Map of reorganized water sector in Croatia. Map of 2 regional companies in Istria (previously 3 – green and blue area is now merged in one company).

CASE STUDY EMILIA-ROMAGNA

In Europe the Water Framework Directive (WFD - EC/60/2000) and its Groundwater Directive (EC/118/2006), together with the regulations for the Common Agricultural Policy pose the regulatory and governance basis for water and groundwater management. In the context of Emilia-Romagna, specific attention has been provided to the regional Rural Development Programme, which in compliance with the WFD allowed to support wetland creation in agricultural soils.

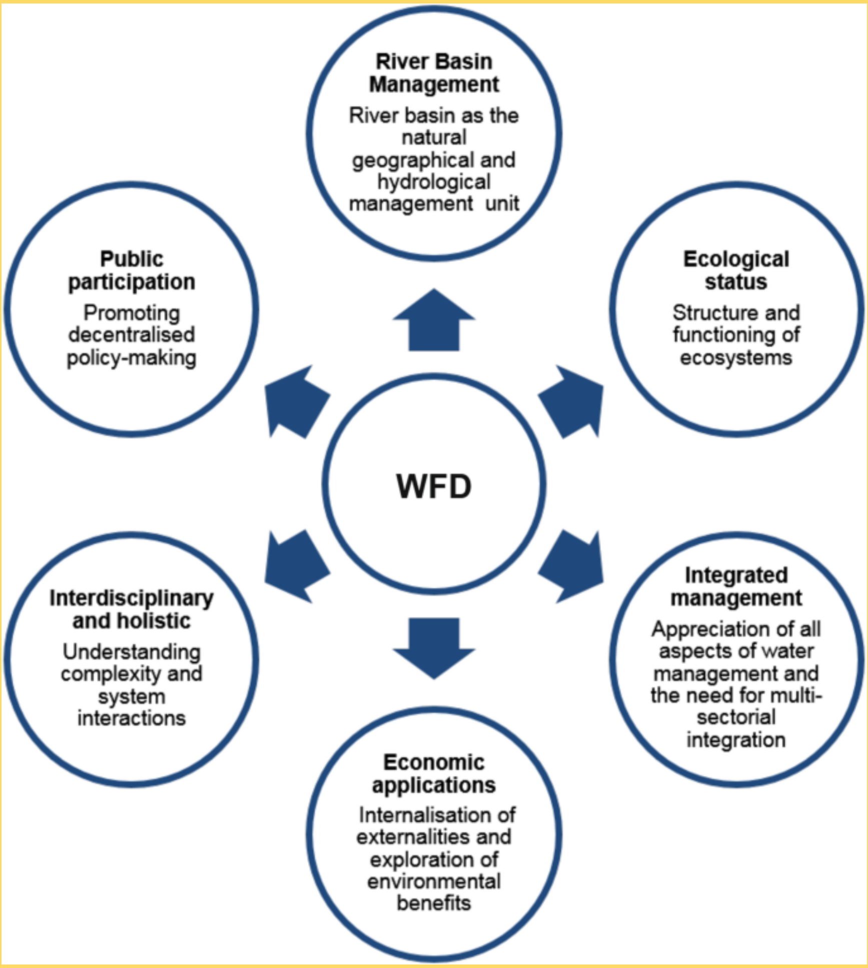


Figure 12. The WFD context (Source: Theodoros Giakoumis & Nikolaos Voulvoulis, 2018)

2 - Data Availability and Monitoring Feasibility

A second fundamental principle in the selection of MAR sites is the availability of data and the feasibility of an adequate monitoring scheme.

Having information *ex-ante* (before MAR implementation) and *ex-post* (during and after operation) is essential for designing the MAR scheme, controlling its functioning, evaluating its hydrological, quantitative and qualitative effects, and supporting the quantification of Blue Credits based on robust evidence.

CASE STUDY ISTRIA

Although the available datasets for southern Istria provide valuable insights into long-term groundwater dynamics, there are several limitations that restrict the accuracy and reliability of current assessments. These gaps are particularly relevant when it comes to the planning, implementation and monitoring of managed aquifer recharge (MAR) measures.

Discontinuity of groundwater level measurements. After the conversion of the regional water supply to the Butoniga reservoir in 2002, systematic monitoring was significantly reduced or discontinued at many wells. For several locations such as Škatari, Ševe and Karpi, data is only available sporadically or for limited periods of time. Even at large wells such as Jadreški and Šišan, the frequency of measurements varied considerably and in some years only a few data points were recorded. This discontinuity makes it difficult to establish consistent long-term trends or to reliably model the response of the aquifer to abstraction or recharge events.

Spatial distribution of the monitoring sites. The data is heavily concentrated on a few wells in operation, while other areas of the aquifer system are poorly characterised. This uneven coverage limits the ability to assess hydraulic gradients, lateral flow directions or the extent of recharge and discharge zones in the region.

In addition, there are inconsistencies in the vertical referencing of groundwater level data. Historical records do not always indicate which reference datum was used (HVRS71 or HRG2000) and the differences between these systems can be more than 90 cm. Without clear geodetic standardisation, it is difficult to integrate historical and current measurements into a consistent model.

Water quality monitoring is also incomplete. Although the concentrations of nitrates, chlorides and other indicators are documented in internal reports, systematic time series are only available to a limited extent. In particular, there is a general lack of real-time monitoring and data collection, which prevents the early detection of contamination or enrichment effects.

These limitations make it clear that the monitoring network urgently needs to be restored and expanded. This includes standardising measurement protocols, improving spatial coverage and restoring continuous time series in both quantitative and qualitative terms. For the implementation of MAR to be effective and safe, decision-makers must have access to reliable, high-resolution data that reflects both short-term fluctuations and long-term trends.

3 – Replicability

A third principle used in MAR selection within the project is the potential for replicability of the intervention. The project case studies selected are not extremely unique or highly specific cases, but rather a representative setting, where: the conditions are typical of a broader class of contexts, and the solutions developed can be transferred and replicated elsewhere.

CASE STUDY ISTRIA

The potential for replicability in the region is high, but can be extended also to any karst region, with the similar challenges, which are many in Mediterranean. The high water demand in the summertime and scarce sources is common for many Mediterranean regions.

CASE STUDY EMILIA-ROMAGNA

As an example for MAR selection, the Emilia-Romagna context poses a valuable positive case study for replicability. Here wetlands have been selected as a MAR category due to their diffusion at the territorial level. Here, only in the basin managed by CER over 4.000 hectares of wet ecosystems have been identified.

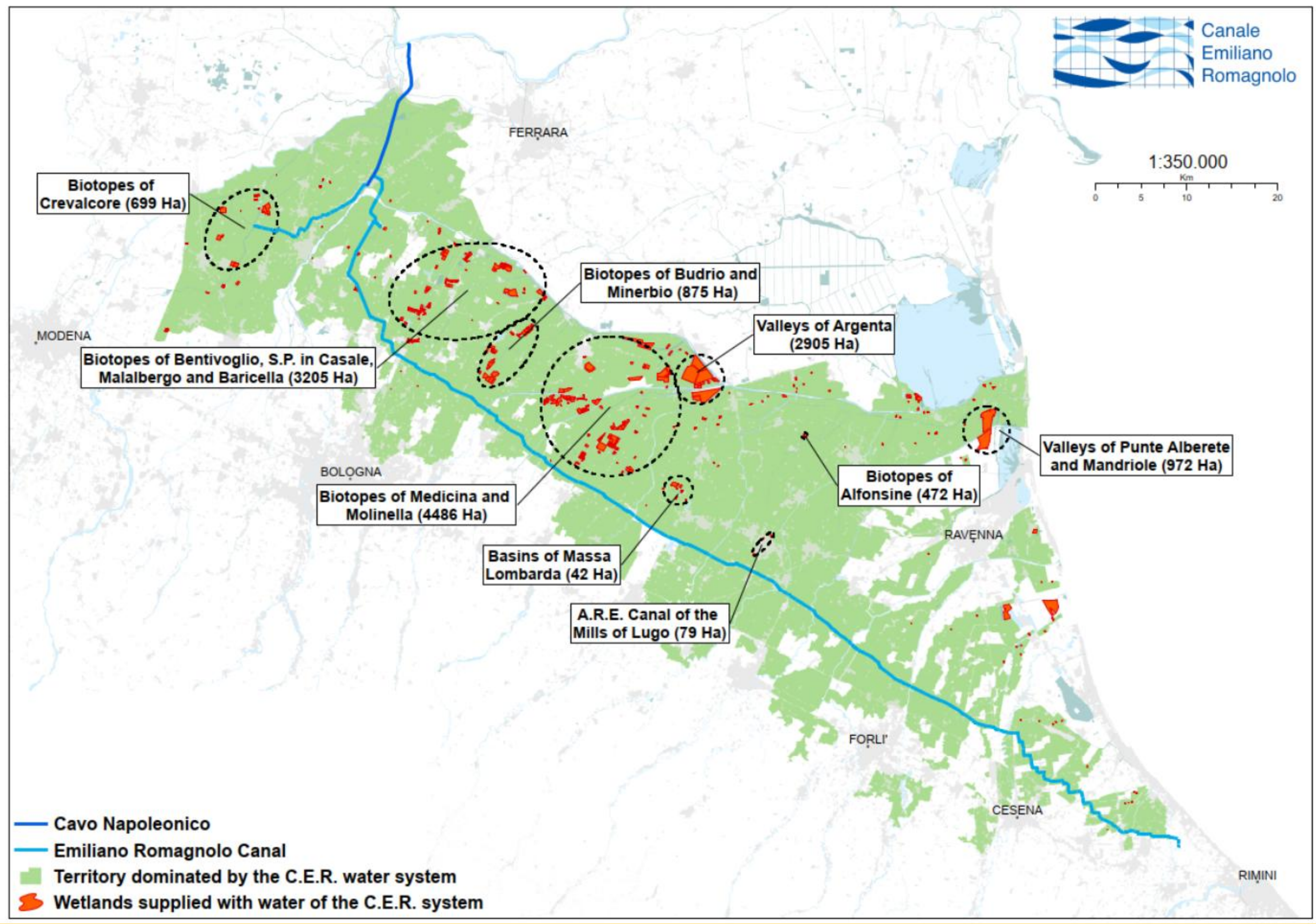


Figure 13. Wetlands identified in the area managed by CER (source: CER elaboration on AGREA and field data)

4 Involvement of the actors

This chapter specifies the actor functions that must be present, how responsibilities should be allocated along the MAR life cycle, and what integrity safeguards are required so that credited claims remain defensible in regulatory and public settings.

4.1 Scope and rationale

Managed Aquifer Recharge is frequently treated as a technical intervention, but the binding constraints are often institutional: authorisations, land access, stable operating mandates, continuous monitoring, and disciplined data governance. In many local settings, monitoring intensity fluctuates with operational intensity and historical records are fragmented across institutions, which weakens baseline definition, additionality assessment, and auditability. A Blue Credits approach is only credible if governance connects field operations to transparent measurement, independent verification, and an auditable registry (Dillon et al., 2022).

4.2 Key actor typology and required functions

A MAR–Blue Credits scheme needs a stable set of functions, regardless of local institutional form. Where incentives conflict, functions must be separated; otherwise the system becomes vulnerable to strategic behaviour and reputational collapse.

1. **Public oversight and permitting.** Authorities define the legal pathway, constraints, and compliance conditions, ensuring MAR supports quantitative objectives without compromising chemical status and protected uses. In the EU, the overarching framework is the Water Framework Directive (European Parliament; Council of the European Union, 2000).
2. **Operator/developer delivery and long-run operation.** A developer/operator (often a utility or equivalent) must design, build, operate, and maintain recharge works and the monitoring system as an integrated unit. Capability is necessary but never sufficient for crediting credibility because the operator controls effort and much of the information relevant to performance (Dillon et al., 2022).
3. **Scientific and technical support.** Scientific partners (universities, geological services, laboratories) maintain a defensible conceptual model, define conservative baselines, identify risks (notably water-quality risks), and design monitoring that supports inference under uncertainty rather than simply producing time series (Dillon et al., 2022).

4. **Data stewardship.** One accountable data steward must enforce QA/QC, metadata discipline, and traceable version control (e.g., vertical datum documentation, sensor-change logs, calibration records, and transparent gap-handling). Without this, measurements can be non-comparable and therefore non-auditable.
5. **Independent verification and registry.** Verification must be independent of operator and buyers, with conflict-of-interest safeguards and full access to primary data and audit trails. A registry must issue and track credits and enforce retirement as the condition for any claim, thereby preventing double counting and narrative inflation (Dillon et al., 2022).
6. **Buyers and local stakeholders.** Buyers finance outcomes through purchase and retirement; landowners, major users, and communities matter where land access and acceptance are binding constraints. Their role is not merely communicative: legitimacy affects the stability of operating mandates and the durability of monitoring arrangements.

4.3 Roles across the MAR life cycle

Roles must be aligned with the life cycle to avoid predictable “handover gaps” that later become disputes.

1. **Preparation and design.** Authorities clarify permitting and constraints; the operator secures land access and demonstrates feasibility consistent with multi-year monitoring obligations; scientific partners define baselines, monitoring designs, and risk controls; verifiers review the evidence plan early so that eligibility and uncertainty rules are not renegotiated after investments are sunk (Dillon et al., 2022).
2. **Construction and commissioning.** Construction readiness must include monitoring readiness: installed sensors, calibration and maintenance plans, data architecture, and reporting protocols that satisfy verification requirements.
3. **Operation and adaptation.** The operator maintains continuous reporting and maintenance; authorities enforce compliance and safeguards; verifiers certify outcomes at defined intervals; the registry issues credits only upon verification and records retirement for claims.
4. **Replication and scaling.** Scaling requires standardised monitoring/reporting templates and, for small systems, aggregation pathways; otherwise fixed MRV and registry costs dominate and replication fails.

4.4 Modalities of engagement and governance

Engagement is most effective when organised through a local steering group that brings together authorities, the operator, scientific partners, the verifier, and the data steward. Delivery can take different forms (utility-led implementation, performance contracting, or results-based procurement), but credibility depends on enforceable accountability and auditability rather than institutional labels. Governance must be defined ex ante, including decision rights, data access, QA/QC responsibilities, corrective-action procedures, and dispute resolution. Renegotiation is most likely in drought years, precisely when incentives to over-claim intensify; pilots should therefore front-load credibility by establishing the steering group, securing land access and operating mandates, agreeing data-sharing and digitisation, validating baseline and monitoring designs with the verifier before construction, and aligning registry issuance and retirement rules before public communication (OECD, 2023).

4.5 Needs, incentives and constraints

The main institutional risk is principal–agent moral hazard: the operator can deliver outcomes but also controls effort, maintenance, and much of the measurement, while holding private information outsiders cannot fully observe. Because higher credited outcomes and lower costs benefit the operator, incentives can favour underinvestment in monitoring and maintenance, strategic reporting, and delayed corrective actions. Crediting therefore cannot rely on intentions; self-reporting is never sufficient for issuance or claims (Dillon et al., 2022). Authorities require defensible evidence of quantitative improvement without chemical deterioration and transparency that withstands public scrutiny. Operators require predictable permitting, clear operational obligations, and cost recovery for monitoring and maintenance, including “quiet-year” costs when continuity remains essential. Developers require stable eligibility rules and a revenue logic that covers recurrent Monitoring, Reporting and Verification (MRV) costs. Scientific partners need continuous data access; data stewards need authority to enforce metadata discipline; verifiers need clear protocols and strict conflict-of-interest safeguards; and buyers need narrow, auditable claims tied to verified outcomes and retirement records. MRV should therefore be transparent, user-friendly, and streamlined (OECD, 2010; OECD, 2023).

CASE STUDY ISTRIA

In Croatia only public actors were included in the testing of possibilities for MAR application: in this case those are companies that are responsible for water supply and wastewater treatment and discharge, and that are now in process of merging. After the test period in Croatia, and regulation of the MAR through legislation it will be possible to involve variety of actors such as private companies or even private persons who have the need for technical quality water for irrigation purposes or some other technical usage.

CASE STUDY EMILIA-ROMAGNA

In the Italian case study, the Baldassari farm acted as the MAR operator, directly managing the operational aspects of the wetland, including water pumping and routine maintenance of the basins, while providing continuous feedback on the seasonal behaviour of the system. Local support was provided by Ferrara Reclamation Consortium, which made available expertise and local knowledge and provided CER and ART-ER valuable insights on hydrological settings, water infrastructures and availability. The involvement of Emilia-Romagna Regional Authority as affiliated partner proved extremely valuable to support the feasibility assessment under current regulations.

5 Quantification of the MAR benefits and monitoring activities

5.1 The Need for Quantification in Blue Credit Systems

MAR systems provide multiple benefits to water resources management and environmental sustainability. To valorize these benefits through blue credit mechanisms, robust quantification and monitoring frameworks are essential. Blue credits represent a market-based instrument that can incentivize MAR implementation by monetizing the environmental and water security benefits generated.

Quantification serves **critical purposes**:

- Demonstrating that MAR achieves intended objectives
- Providing empirical basis for credit generation and trading
- Proving benefits would not occur without MAR intervention
- Translating technical outcomes into understandable benefits
- Supporting cost-benefit analyses and investment decisions

The challenge lies in developing quantification approaches that are scientifically rigorous yet practical to implement, particularly in resource-constrained settings.

Framework for MAR Benefit Categories

MAR benefits can be categorized into primary water benefits and environmental co-benefits:

Primary water benefits:

- Increased water availability (additional recharged volume)
- Improved water security and supply reliability
- Groundwater level stabilization or recovery
- Enhanced storage capacity utilization

Environmental co-benefits (ecosystem services):

- Water quality improvement
- Biodiversity enhancement in recharge areas
- Reduction of saltwater intrusion in coastal aquifers
- Maintenance of groundwater-dependent ecosystems
- Soil quality improvement
- Microclimate regulation

For blue credit systems, quantification must establish additionality: the benefits would not have occurred without the MAR intervention. This requires baseline establishment, ongoing monitoring, and rigorous attribution of observed changes to MAR activities.

5.2 Quantification Methodologies for Water Benefits

The fundamental metric for MAR benefit quantification is the volume of additional water successfully recharged to the aquifer. This requires a comprehensive water balance.

Water Balance Components

Inflow:

- Source water volume
- Natural infiltration in recharge area

Outflow:

- Actual infiltration/injection to aquifer
- Evaporation from infiltration basins
- Vegetation evapotranspiration
- Surface runoff not captured
- System losses

Measurement Techniques:

1. Direct measurement:
    - Flow meters on intake structures
    - Weirs and flumes for surface water diversions
    - Injection well flow meters for direct recharge systems
    - Groundwater level monitoring with pressure transducers
2. Indirect estimation:
    - Water table fluctuation method: $\Delta V = Sy \times A \times \Delta h$
        - Where Sy = specific yield, A = area, Δh = water level change
    - Tracer studies for infiltration rate determination
    - Geophysical methods for moisture content changes
    - Remote sensing (satellite-based soil moisture, evapotranspiration)
3. Numerical modeling:
    - Groundwater flow models (for distinguishing MAR effects from natural variability)
    - Coupled surface-groundwater models for infiltration basins
    - Projects long-term benefits beyond monitoring period

Baseline Establishment

Quantifying additional water requires comparison against a baseline scenario:

- Historical data analysis
- Control wells outside MAR influence zone
- Counterfactual modeling (what would have occurred without intervention)

Key Considerations

- **Aquifer type matters**: Karst systems have higher uncertainty (factor of 2-5) due to heterogeneity compared to porous media aquifers
- **Temporal variability**: High natural variability requires longer monitoring periods
- **Spatial representativeness**: Monitoring density must reflect hydrogeological complexity

5.3 Practical recommendations

For new MAR projects seeking blue credit valorization:

1. **Design monitoring for dual purposes from outset:**
    - Operational management (real-time data for adaptive operation)
    - Benefit verification (data quality and completeness for certification)
    - Avoid costly retrofits by planning monitoring infrastructure early
2. **Invest strategically in site characterization:**
    - Hydrogeological understanding reduces uncertainty and monitoring costs long-term
    - Tracer studies, hydraulic testing
    - Identify unsuitable sites early (e.g., rapid karst conduits with poor treatment)
3. **Adopt standardized protocols:**
    - Align with emerging blue credit standards and water monitoring best practices
    - Use established methods - facilitates verification and comparison across projects
4. **Integrate modeling with monitoring:**
    - Models extend point measurements to system-wide benefits
    - Essential for long-term projections beyond monitoring period
    - Calibrate with monitoring data, validate predictions, iterate
5. **Engage stakeholders and institutions early:**
    - Regulatory authorities (permitting, blue credit framework)
    - Potential buyers (understand needs and willingness-to-pay)
    - Certification bodies (ensure monitoring design meets requirements)
    - Technical capacity building alongside infrastructure development
6. **Plan for long-term monitoring commitment:**

   - Blue credits require ongoing verification (annual or multi-year cycles)
   - Secure dedicated funding: Link to operational budgets, water tariffs, or buyer contracts
   - Avoid dependency on short-term project grants

7. **Be transparent about uncertainty:**
   - Document assumptions, data gaps, uncertainty ranges
   - Conservative credit issuance builds market credibility
   - Ongoing validation and model updating as data accumulates

CASE STUDY ISTRIA

In this Case study on the example of the pilot area of Southern Istria, the complex issue of the discharge of treated wastewater into the karst subsoil, its transfer and the impact on the quality of groundwater of the coastal aquifer were analyzed to examine the possibility of applying MAR with treated waste water on the coastal area of Vodnjan in the area of Southern Istria. By applying tracing methods, and monitoring the dynamics of groundwater fluctuations, as well as monitoring changes in its quality in different hydrological conditions, knowledge has been obtained not only about the functioning of the part of the southern Istria watershed that is in the immediate vicinity of the Loborika wastewater treatment plant (WWTP), but also in the wider potentially influential area. The results of the tracer test show a possible direction of drainage of the waters of this area towards the well Tivoli, which was expected, given the current knowledge of the hydrogeological structure. Very low apparent groundwater flow velocities of 0.09 cm/s were determined, and accordingly low mobility of the discharged treated wastewater. This, as well as the dynamics of groundwater level fluctuations, indicates a longer time of infiltration of treated wastewater into the underground through the vadose zone, and better effects of their self-treatment. The very long flow time of the tracer, and it’s still high concentration at the location of the infusion site at the Loborika WWTP, indicates the need for further control sampling and detection of tracer concentrations in groundwater.

The figures represent data of tracer test results in the period from 1st of April 2025 until January 2026.

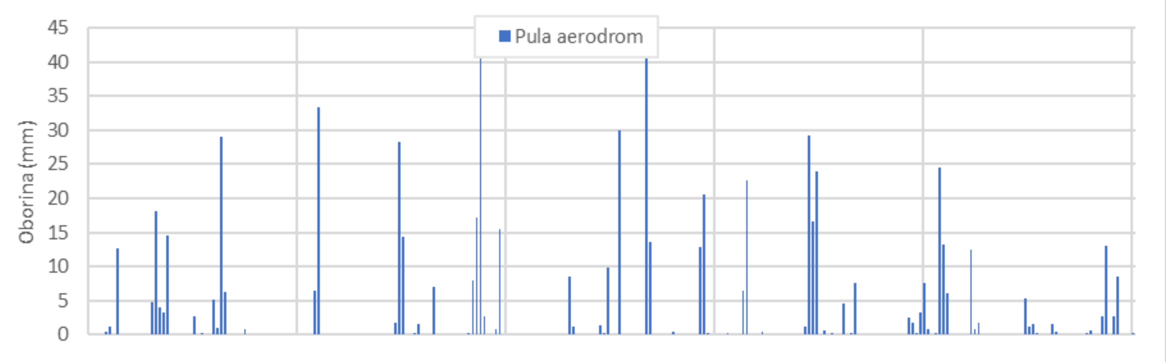


Figure 14. Precipitation at Pula airport

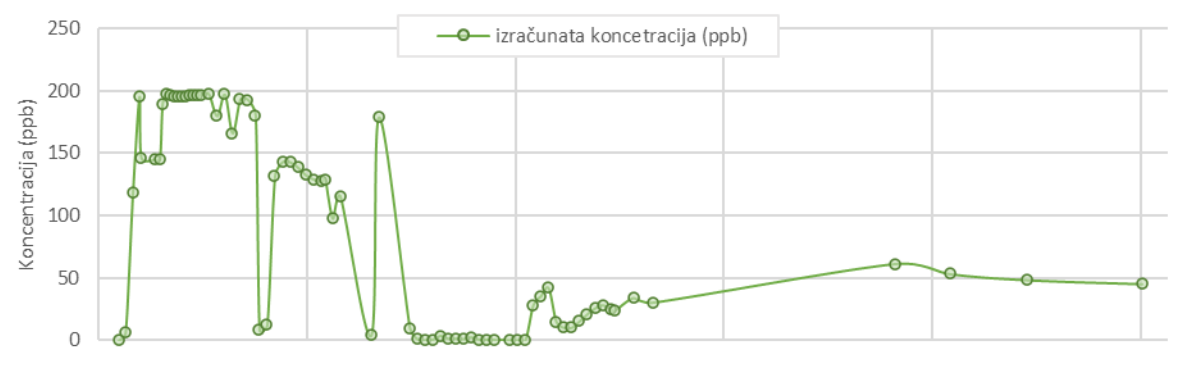


Figure 15. Concentration of tracer agent in Loborika control well

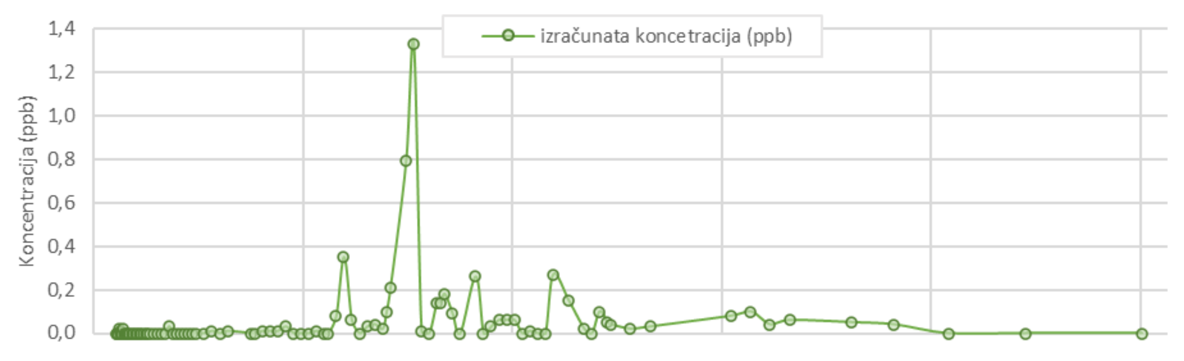


Figure 16. Concentration of tracer agent in Tivoli well

It was also found that the WWTP in Loborika, although not fully functional in terms of consumer connection and despite extremely high input loads, achieved very good treatment effects in some cases. On the other hand, under the conditions of more moderate inlet concentrations, the efficiency of the treatment was weaker, with some output parameters exceeding the prescribed limit values. In separate study that was performed analyzing possible improvement of wastewater treatment process it is concluded that additional filtration should be applied to achieve better and more reliable results.

CASE STUDY EMILIA-ROMAGNA

In the Italian case study, the quantification of MAR benefits was structured as a rigorous and integrated process based on direct field measurements, continuous monitoring and independent estimation methods, with the aim of obtaining a technically sound, transparent and verifiable value of groundwater recharge. The monitoring strategy was designed to capture both the temporal dynamics of the aquifer response and the spatial variability of soil and subsoil conditions, ensuring the robustness of the recharge assessment and its suitability for subsequent certification within the Blue Credits framework. The monitoring system was implemented through the installation of three piezometers within and along the margins of the agricultural wetland, positioned to represent different hydraulic and pedological conditions and to capture differentiated responses of the shallow aquifer to controlled wetland management. All piezometers were equipped with automatic TD Diver sensors, allowing continuous, high-frequency recording of groundwater pressure and temperature. One of the piezometers located in Area III, where the interaction between surface water and groundwater is most pronounced, was also equipped with a CTD Diver capable of recording electrical conductivity (Figure 3).

Figure 17. TD and CTD Divers installed in the piezometers in the study area for monitoring groundwater level, temperature, and conductivity

This configuration made it possible to monitor not only groundwater level variations, but also qualitative changes in groundwater, with particular reference to potential salinity dilution effects associated with the infiltration of low-salinity surface water stored in the wetland. Monitoring activities started in spring 2025, and the analysed dataset covers the period from April to November 2025, corresponding to the active management phase of the basins. The use of Diver technology ensured objective and continuous monitoring, enabling the detection of rapid piezometric responses following basin filling events and allowing the separation of the effects of managed recharge from those related to meteorological inputs and seasonal variability (see Graph). The high temporal resolution of the measurements proved essential for supporting the interpretation of groundwater dynamics and for providing traceable and reproducible data suitable for third-party verification. To support the interpretation of piezometric data and the estimation of infiltration fluxes, in situ permeability tests were conducted using both Auger Hole and Inverse Auger Hole methods. These tests provided estimates of saturated hydraulic conductivity in the different areas of the wetland and highlighted a marked spatial heterogeneity in soil hydraulic properties.

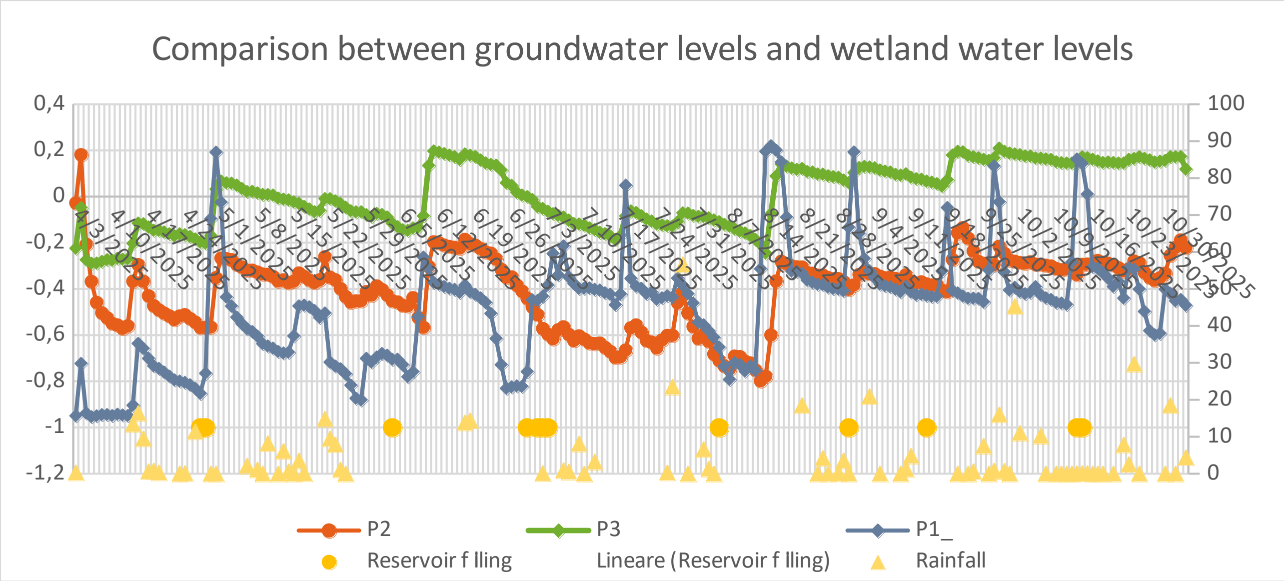


Figure 18. Comparison of groundwater level trends recorded in the three piezometers

The first quantitative estimate of groundwater recharge was obtained through a water balance of the wetland basins, reconstructed on the basis of actual operational data, including pumped inflows, residual stored volumes and estimated evaporative losses. The volumetric balance method yielded an estimated recharge of approximately 12,400 m³ over the monitoring period, corresponding to about 5,370 m³/ha when referred to the effectively flooded surface.

A second, independent estimation approach was based on the analysis of water level decay in the basins during periods without significant precipitation. By evaluating the average daily drawdown of surface water levels and accounting for evapotranspiration losses, this method provided a slightly lower recharge estimate of approximately 10,100 m³, corresponding to about 4.370 m³/ha (following Table).

Infiltrated volume per hectare, method 1	(m^3/ha)	5.370,42
Infiltrated volume per hectare, method 2	(m^3/ha)	4.368,74

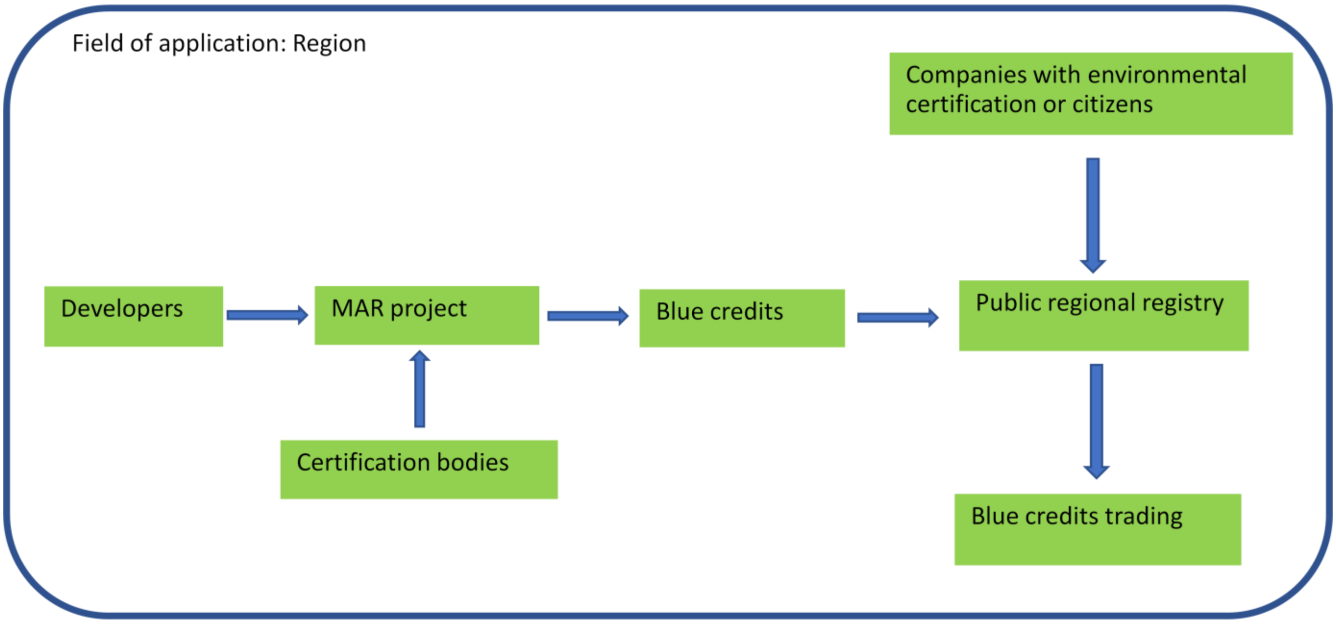
The two approaches therefore define a plausible recharge range between 39% and 47% of the total volume introduced into the basins. The convergence of results obtained through independent methods confirms the effectiveness of the agricultural wetland as a Managed Aquifer Recharge system in the Italian case study and provides a solid quantitative basis for the subsequent valorisation of the environmental benefit through the Blue Credits mechanism.

6 Blue credits mechanism feasibility

The Blue Recharge mechanism designed for the blue credits is composed by the following steps:

1. implementation of a MAR project
2. quantification of the additional benefits derived from the implementation of the MAR project
3. certification of the environmental benefits and definition of the amount of blue credits
4. upload of the project on the regional platform acting as registry
5. access to the platform by the buyers after qualification
6. trading of the blue credits and monitoring of projects' benefits development

The scheme is represented in the next figure.



The described steps have to be developed in consideration of preliminary conditions and defined responsibilities.

Implementation of a MAR project

To valorize a MAR project through blue credits is necessary to prepare a document describing some items:

- territorial features as geology, pedology, hydrogeology, morphology and topography
- groundwater conditions (e.g. confined or unconfined aquifer, groundwater level and seasonality, groundwater quality)

- ownership and use rights for the land
- MAR techniques
- monitoring activity

Is necessary to identify a subject responsible for the implementation and management of the MAR, called “developer”. The developer is the owner of the blue credits related to the implementation of the MAR.

Quantification of the additional benefits

To quantify the environmental benefits to be valorized through blue credits is necessary to focus on the concept of “additionality”, that is an approach that valorize the positive impacts generated by the project that would not have occurred in its absence. To quantify these type of benefits the developer has to define a “baseline”, that is a model representing the groundwater level and volume trend during time, without MAR technique’s implementation.
The baseline has to be compared to the measured groundwater level and volume trend derived from the MAR implementation (so called “project scenario”).
For both the baseline and the project scenario, also the co-benefits has to be assessed or estimated. The co-benefits could be different in consideration of the MAR techniques and the context. Examples of co-benefits are: water purification, biodiversity preservation, carbon sequestration and flood mitigation.

Certification of the environmental benefits

To generate blue credits, the environmental benefits of the MAR project has to be verified by an independent third-party, as a certification body. The verification has to consider:

- the quality of the project
- the documentation’s management
- the correctness of the calculation of additional water recharge and other co-benefits
- the monitoring of the environmental benefits
- the eventual negative impacts of the project

The main objective of the verifier is to estabilish the amount of additional groundwater volume, expressed in cube meters. This volume is necessary to define the amount of blue credits (1 m^3 of water = 1 blue credit).
In the project's document, a multi-year scenario (e.g 10-15 years) has to be defined, with a forecast of the water volume changing. The blue credits can be sold only after the measurement of the real occurred recharge.
The trading is possible only for blue credits derived by a recharge realized before the publication on the registry.

The regional registry

The Blue Recharge approach considers the institution of a registry managed by a public authority and acting at regional level. The trading is possible between buyers and sellers located both in the region where the MAR project is implemented.
The registry can be managed by a public administration (e.g. Regional Authority, River basin Authority, Water management Authority) directly or indirectly (e.g. through participated agency).

Qualification of the buyers

To access to the MAR project's information and acquire blue credits, the buyer has to register to the platform. If the buyer is a company, the registration foresees a qualification that has to demonstrate a commitment to the water sustainable management. The Blue Recharge approach is based on the environmental certifications of organizations and products (e.g. AWS, EMAS, ISO14001, ISO14046, EPD, EU ECOLABEL) as tool to demonstrate the commitment. The registry contains a section in which the company must enter information relating to its certifications. If the buyer is a citizen, no qualification is foreseen.

Trading and monitoring

The registry is an online platform that displays MAR projects and the related blue credits. Both the sellers and the buyers have to be registered to the platform, but the financial transactions are managed directly by them out of the platform. A communication from the sellers and the buyers to the registry manager permits to keep updated the amount of credits generated by a MAR project, considering the yearly additional recharge and the progressive sales.

CASE STUDY EMILIA-ROMAGNA

In the Italian case study, the feasibility of the Blue Credits mechanism was verified through the complete and operational application of all phases foreseen by the model developed within the BLUE RECHARGE project in a real agricultural context, based on an existing green infrastructure and on field-measured monitoring data.

The first operational step concerned the definition of recharge additionality, that was assessed by comparing the project scenario, characterized by the presence and active management of the agricultural wetland, with a reference condition representative of the absence of MAR.

The reference scenario was reconstructed using historical data from the regional piezometric network, in particular from a station located upstream of the study area and not directly influenced by the wetland. This made it possible to describe the natural behaviour of the shallow aquifer under comparable pedological and climatic conditions, but without the infiltrative contribution generated by the basins.

The comparison between the two scenarios allowed the attribution of an annual additional recharge to the wetland ranging between approximately 10,100 and 12,400 m^3, which was assumed as the environmental benefit directly attributable to MAR.

Once the additional recharge was quantified, the benefit was expressed in Blue Credits according to the equivalence principle adopted in the project, which assigns one credit for each cubic metre of water recharged in addition to the baseline.

In the Italian case study, the reference volume for valorisation was assumed to be approximately 12,400 m^3/year, corresponding to the same number of Blue Credits potentially placeable on the market, subject to verification and certification. This step represented a key element in demonstrating that the ecosystem service provided by the wetland can be translated into a standardized economic unit that is understandable and comparable.

The feasibility of the Blue Credits mechanism was further tested through the application of an independent audit. In the Italian case study, a certification body was appointed to develop and apply a specific verification protocol for the wetland-based MAR project.

The potential market has been explored analysing the companies with proper environmental certification in Emilia-Romagna, that are about 4.500. They represent potential qualified buyers.

Finally, also the appeal of the scheme has been analysed through interview with testimonial companies, belonging to the agrifood sector.

7 Conclusions

The comparison table below summarizes the operative solutions adopted in the Italian and Croatian case studies about the issues described in the 2-6 chapters.

Activity	Italy case study	Croatia case study
MAR objectives	Controlled recharge of the shallow phreatic aquifer in an agricultural area of the Po Delta, mitigation of saltwater intrusion, support to climate resilience, improvement of groundwater quality, valorisation of wetland ecosystem services and support to biodiversity.	Rising of groundwater levels to sustainable levels. MAR will increase the storage capacity for use during dry seasons or droughts. MAR can push back saltwater, protecting freshwater aquifers and preventing saltwater intrusion, so that still can be used for irrigation. Prevents of ground from sinking due to over-extraction.
Selection of the MAR	Selection of an existing agricultural wetland in the Mezzano Valley (Baldassari farm), based on hydrogeological, pedological and environmental analyses, availability of historical and current data, simplicity of the hydraulic system, presence of existing infrastructure and high potential for shallow aquifer recharge.	Used criteria are: (1) sufficient distance from urbanised areas to minimise contamination risk; (2) existing infrastructure that can be repurposed for infiltration or monitoring; (3) accessibility for regular maintenance and control; (4) local geological conditions favourable to infiltration, such as fractured or weathered carbonate rocks; and (5) vertical and horizontal hydraulic connectivity to the broader aquifer system
Involvement of the actors	Direct involvement of the farm owning the site, the Canale Emiliano Romagnolo (CER) Reclamation Consortium providing technical support, monitoring activities and laboratory analyses, regional authorities for groundwater data and institutional framework, and an	Only public actors were included: in this case those are companies that are responsible for water supply and wastewater treatment and discharge, and that are now in process of merging. After the test period in Croatia, and regulation of the MAR through legislation it will be possible

	independent certification body for project verification.	to involve variety of acters such as private companies or even private persons who have the need for technical quality water for irrigation purposes or some other technical usage.
Quantification of the MAR benefits and monitoring activities	Continuous groundwater level monitoring through piezometers equipped with TD and CTD Divers, chemical and physical water analyses, field permeability tests (Auger Hole and Inverse Auger Hole), volumetric water balance of the wetland basins and Piezometric decay, estimation of a net groundwater recharge of approximately 12,400 m³ over the annual monitoring period.	Continuous groundwater level monitoring through piezometers equipped with TD and CTD Divers, chemical physical and micro-biological water analyses, assessed possibility of MAR applying in the areas where water is used only for irrigation and technical use.
Blue credits mechanism feasibility	Full testing of the Blue Credits mechanism, development and application of an audit protocol by a certification body, definition of additionality through comparison between baseline and project scenarios, identification of the regional potential market for blue credits, interview with testimonial enterprises and overall positive assessment of the system feasibility.	Presentation of the system to regional key actors in order to collect preliminary feedback.

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