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BLUE RECHARGE

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BLUE RECHARGE

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Report

Environmental impact of the case studies

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SUMMARY

This Environmental Impact Assessment evaluates two pilot demonstrations of Managed Aquifer Recharge (MAR) developed under the INTERREG Italy-Croatia BLUE RECHARGE project. The assessment is based on comprehensive monitoring results presented in project deliverables D.2.1.1 Report – Case study Italy and D.2.2.1 Report – Case study Croatia. Both MAR interventions utilize water designated for non-potable purposes (irrigation, technical/industrial applications, and saltwater intrusion barrier management). The recharged groundwater is not intended for direct human consumption or potable water supply. Aquifer replenishment serves agricultural resilience, ecosystem support, and coastal aquifer protection objectives

Case Study Italy – Mezzano Valley (Po Delta, Emilia-Romagna) implements nature-based MAR through strategic use of existing wetland ecosystems as infiltration basins for shallow alluvial aquifer recharge. The pilot site at Baldassari Farm demonstrates controlled basin filling provides quantifiable groundwater level responses. Hydraulic characterization confirms favorable site conditions and effective aquifer-wetland interaction without negative environmental impacts. Regional upscaling potential: ~10 million m^3/year supplemental recharge capacity equivalent to water demand of 25,000-30,000 people.

Case Study Croatia – WWTP Loborika (Southern Istria) demonstrates wastewater-based MAR in challenging coastal karst aquifer environment. The pilot utilizes tertiary-treated municipal effluent for subsurface infiltration through injection wells. Comprehensive characterization integrating five independent methodologies (tracer testing, infiltration capacity testing, Radon-222 analysis, continuous groundwater monitoring, isotopic baseline characterization) confirms site suitability: matrix-dominated slow flow regime, multi-month to multi-year residence times providing, no rapid pathways to major water sources, and infiltration capacity exceeding WWTP discharge.

Both case studies confirm MAR as environmentally beneficial climate adaptation strategy providing multiple synergistic benefits: groundwater quantity enhancement and drought resilience, saltwater intrusion mitigation through freshwater hydraulic barriers, natural water quality improvement via soil aquifer treatment, protection of existing water sources, and demonstration of sustainable circular water economy. Potential negative impacts (agricultural waterlogging, aquifer clogging, contaminant mobilization) are assessed as low risk and

manageable through design features, operational protocols, and monitoring-based adaptive management.

Environmental Impact Conclusion: Italy case study assessed as HIGHLY POSITIVE with recommendation for full regional implementation. Croatia case study assessed as HIGHLY BENEFICIAL with acceptable manageable risks and recommendation to proceed with operational MAR system under precautionary monitoring framework. Both pilots provide transferable blueprints for Mediterranean coastal regions and global karst aquifer systems facing water scarcity, seawater intrusion, and climate change challenges.

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1 CASE STUDY ITALY

The Italian component of the BLUE RECHARGE project implements a nature-based solution (Nbs) for managed aquifer recharge (MAR) through strategic use of wetland ecosystems in the Mezzano Valley, located in the Po Delta region of Emilia-Romagna. This Environmental Impact Assessment (EIA) evaluates the environmental consequences, benefits, and risks associated with utilizing constructed and restored wetlands as infiltration basins to enhance groundwater recharge in shallow alluvial aquifers.

The shallow aquifer in this region faces critical water resource challenges including:

- groundwater over-abstraction for agricultural irrigation, threatening aquifer sustainability;
- saltwater intrusion from the Adriatic Sea and Comacchio lagoons, degrading freshwater quality and causing soil salinization;
- land subsidence from historical water table lowering; and
- climate change-driven increases in drought frequency and intensity.

The BLUE RECHARGE project addresses these challenges by leveraging the >4,000 hectares of existing wetlands constructed in the Canale Emiliano Romagnolo (CER) territory under Rural Development Programmes (RDP) as multi-functional ecological infrastructure. By optimizing water management in these wetlands, the project aims to:

- reduce saltwater intrusion through freshwater hydraulic barriers;
- improve groundwater quality through natural filtration and dilution;
- maintain wetland biodiversity and ecosystem services while enhancing hydrological function; and
- develop replicable nature-based water management models for Mediterranean deltaic systems.

1.1 Study Area Characteristics - Mezzano Valley

The Mezzano Valley pilot site (Province of Ferrara) represents the heart of the Po Delta reclaimed landscape. Specifically, the Baldassari Farm wetland complex was selected for intensive monitoring based on optimal hydrogeological conditions. Key characteristics of the pilot site are summarized in the Table 1.1.

Parameter	Characteristics
Location	Mezzano Valley, Po Delta, Province of Ferrara, Emilia-Romagna
Total wetland area	8.30 hectares (3 interconnected basins)
Wetland water depths	Area I: 10-20 cm | Area II: ~30 cm | Area III: 10-50 cm (Fig. 1.1)
Water management	Monthly controlled filling from irrigation canal network
Geology	Holocene fluvio-palustrine sediments; sandy loam to silty loam texture
Soil classification	Boccaleone silty loam and Garusola sandy loam complexes
Water salinity	563 µS/cm @ 27.1°C (LOW - favorable for freshwater recharge)
Groundwater depth	~1.0-1.5 m below ground surface (shallow unconfined aquifer)
Site suitability	EXCELLENT - Low salinity, favorable soil permeability, existing infrastructure

Table 1.1: Baldassari Farm wetland pilot site characteristics

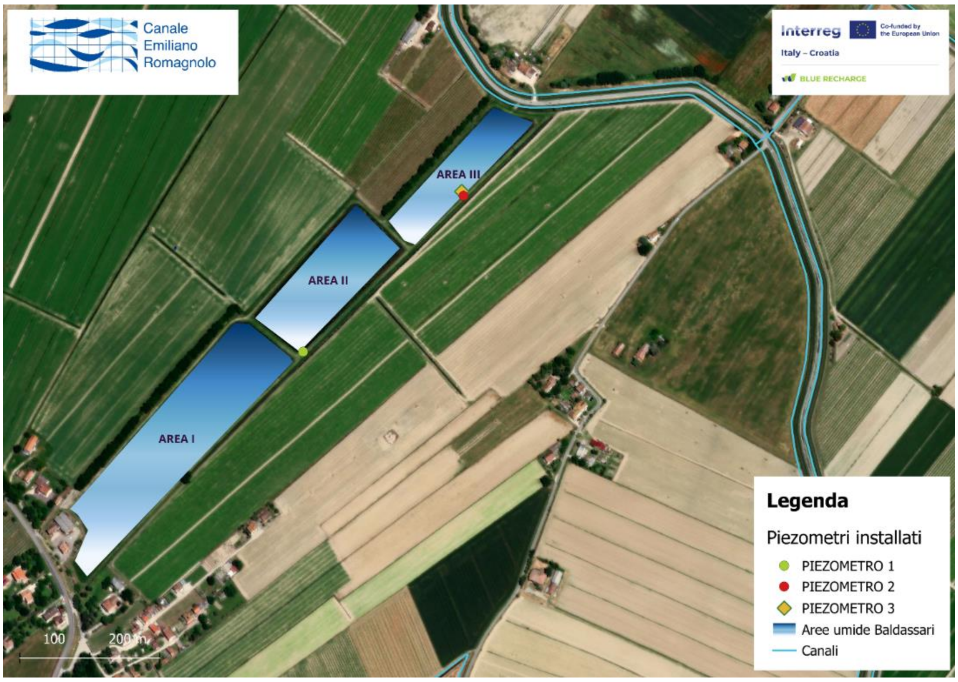


Figure 1.1. Wetland area of the Baldassari Farm.

1.2 Monitoring Program and Methodology

A comprehensive field monitoring program was implemented in the period June - December 2025.

1.2.1 Instrumentation

- Three piezometers equipped with TD Diver pressure transducers (10-minute recording intervals) measuring groundwater level, temperature, and electrical conductivity: Piezometer P1: Installed within Area II wetland basin (sandy soils, high permeability); Piezometer P2: Located on Area III embankment (transition zone); and piezometer P3: At wetland margins in Area III (silty loam soils, lower permeability).
- Regional monitoring network integration: Piezometer 43FE (upstream) and 18FE (downstream) providing long-term context.

- Meteorological data from ARPAE Umana station (hourly precipitation).
- Basin filling schedule records from the farm operator.

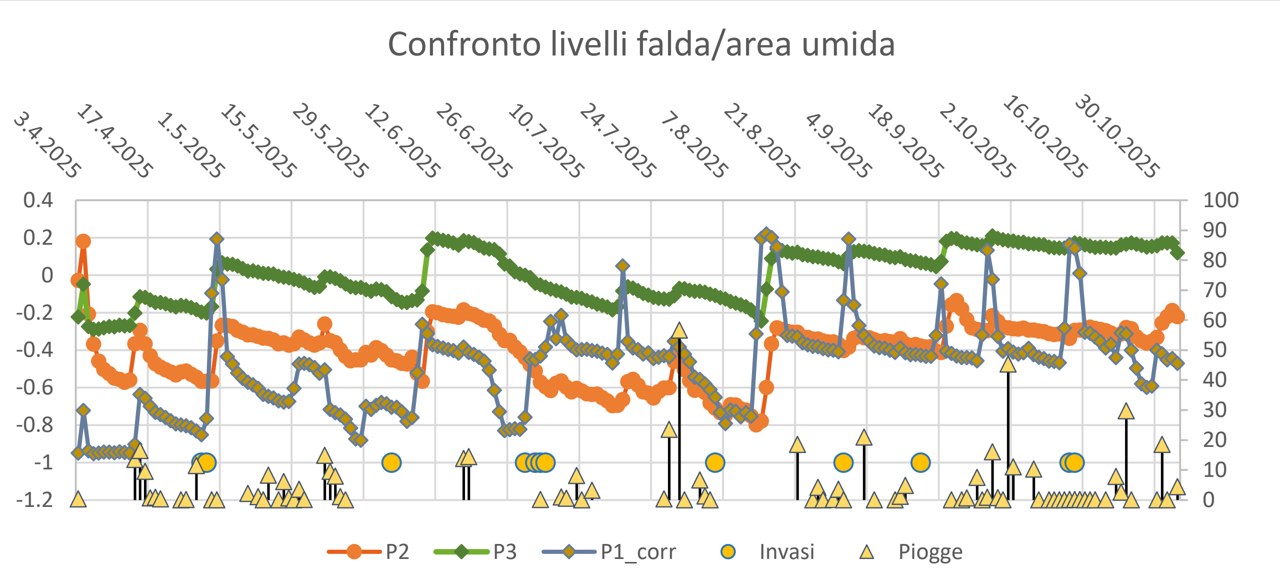


Figure 1.2. Comparative groundwater level trends in piezometers (P1-Area II within wetland, P2-Area III embankment, P3-Area III margin) demonstrating spatial heterogeneity in aquifer response to wetland filling events, Summer-Autumn 2025

1.2.2 Hydraulic characterization

- Auger Hole Method (Hvorslev) slug tests conducted November 3, 2025.
- Inverse Auger Hole Method for unsaturated zone analysis.
- Determination of saturated hydraulic conductivity (K_{sat}) for recharge modeling.

1.2.3 Pedological assessment

- Two soil cores extracted during piezometer installation (Baldassari 1: 200 cm depth, Baldassari 2: 235 cm depth).
- Horizon description following Emilia-Romagna Regional Field Guide (2020).
- Texture analysis (USDA classification), carbonate content, hydromorphic features.

- Attribution to regional Soil Typological Units (UTS) using Emilia-Romagna Soil Catalogue.

1.3 Key Findings - Groundwater Response to Wetland Recharge

Monitoring data analysis revealed clear and quantifiable groundwater level responses to wetland basin filling events.

1.3.1 Basin Filling Controls Groundwater Levels

A direct correlation exists between wetland filling events and piezometric rises, with basin water inputs representing the dominant recharge source during monitored periods. This correlation is especially pronounced in Piezometer P1 (Area II - sandy soils) where:

- groundwater level peaks occur shortly after basin filling, indicating rapid infiltration;
- marked water table rises observed following major filling events; and
- precipitation events show secondary influence compared to controlled basin inputs.

In contrast, Piezometers P2 and P3 (Area III - silty loam soils) exhibit attenuated and delayed responses, consistent with lower hydraulic conductivity. However, all three piezometers demonstrate sensitivity to surface water regime, confirming effective aquifer-wetland interaction.

1.3.2 Hydraulic conductivity results

Field hydraulic conductivity tests (November 3, 2025) quantified saturated hydraulic conductivity (K_{sat}) revealing significant spatial heterogeneity:

- Area II (sandy loam soils): K_{sat} = 0.10-0.27 m/day
- Area III (silty loam): K_{sat} = 0.003-0.02 m/day
- Interpretation: Area II exhibits significantly higher infiltration capacity, explaining rapid piezometric responses. Area III provides slower, sustained recharge with better water retention.

These K_{sat} values are typical of alluvial deltaic soils and confirm site suitability for MAR operations. The spatial variability allows optimization: high-permeability zones maximize recharge volume, while lower-permeability zones extend residence time for natural filtration.

1.3.3 Pedological findings

- Baldassari 1 (Area II): Matched CANALE DEL SOLE silty loam (CDS1) - former tidal channel levee; sandy texture maintained to 2 m depth (50%+ sand); pronounced hydromorphic features from 25 cm indicating frequent saturation.
- Baldassari 2 (Area III): Matched BOCCALEONE silty loam (BOC1) - fluvial levee deposits; silty-loam horizons beyond 135 cm; thin interbedded peat layer detected (historic wetland environment).
- Significance: Good correspondence with regional soil classification validates site selection. Transition zone geology between Po di Primaro levee and reclaimed lagoon creates ideal conditions for controlled infiltration.

1.4 Preliminary Recharge Quantification

Two complementary methods were employed to estimate groundwater recharge from wetland operations.

1.4.1 Method 1 - Water Balance Approach

Recharge = Total inflow − Total evapotranspiration − Residual volume in basins

Preliminary calculations for monitored period (Summer-Autumn 2025) indicate:

- Estimated recharge: ~35-50% of basin inflow volume converts to groundwater recharge
- Evapotranspiration losses: ~30-45% (seasonally variable)
- Surface runoff/storage: ~10-15%

1.4.2 Method 2 - Hydraulic Conductivity-Based Estimation

The second method utilizes measured K_{sat} values to calculate potential vertical infiltration flux. Quantitative results for this method are currently in progress and will be integrated into the numerical groundwater flow model to simulate infiltration processes and validate water balance estimates (Method 1).

Preliminary results show promising alignment between water balance estimates (Method 1) and observed piezometric responses consistent with measured hydraulic conductivities. Final numerical modeling (Method 2, in progress) will provide quantitative validation and support development of the Blue Credits framework for recognizing and compensating wetland ecosystem services for water resource management.

2 ENVIRONMENTAL IMPACT ASSESSMENT - Case Study Italy

2.1 Positive Environmental Impacts

The wetland-based MAR approach generates multiple synergistic environmental benefits:

2.1.1 Groundwater quantity enhancement

- **Increased aquifer storage:** Pilot site monitoring (Baldassari Farm, 8.3 ha) demonstrates ~12,400 m^3 recharge over 7-month period (April-November 2025), equivalent to ~210 m^3/ha/month supplemental groundwater storage. Extrapolating to the CER regional wetland network (>4,000 ha), full implementation represents potential annual recharge of ~10 million m^3, equivalent to water demand of ~25,000-30,000 people
- **Drought resilience:** Controlled recharge during wet periods builds aquifer reserves for dry season extraction, reducing agricultural irrigation stress. Piezometric monitoring confirms direct correlation between basin filling events and groundwater level rises, with Area II (sandy soils) showing rapid response and Area III (silty loam) providing sustained slower recharge.
- **Climate change adaptation:** Nature-based MAR provides flexible storage capacity to buffer against climate change impacts, including saltwater intrusion from sea-level rise and increased precipitation variability. Strategy aligns with EU objectives for climate adaptation and sustainable water management.

2.1.2 Saltwater intrusion mitigation

- **Salinity gradient context:** Po Delta faces critical saltwater intrusion challenge from the Adriatic Sea and Comacchio lagoons, exacerbated by groundwater over-abstraction and sea-level rise. Wetland water quality varies significantly across sites: Baldassari 563 µS/cm (low salinity) vs. Nalin 1,021 µS/cm and Eurovo 1,460 µS/cm (moderate salinity), reflecting spatial salinity gradients.

- **Recharge with low-salinity water:** Baldassari site selected partially due to favorable low electrical conductivity (563 µS/cm), enabling freshwater recharge that can dilute ambient groundwater salinity. Sustained wetland infiltration elevates water tables, potentially creating hydraulic conditions that oppose further seawater encroachment.
- **Soil salinization risk:** The Mezzano Valley faces constant risk of soil salinization, especially during drought and groundwater level drawdown periods. MAR operations that maintain higher groundwater levels may help mitigate this agricultural sustainability challenge by reducing capillary rise of saline water into root zones.

2.1.3 Water quality improvement

- **Natural filtration:** Infiltration through wetland soils (~1.3 m vadose zone at Baldassari based on 130-135 cm water table depth) provides mechanical filtration as water percolates through loam and sandy loam horizons before reaching the shallow aquifer. Pedological investigations documented soil texture ranging from sandy loam (Area II - higher permeability) to silty loam (Area III - finer texture).
- **Surface-groundwater quality differentiation:** Preliminary monitoring indicates significant variations in turbidity and conductivity levels between surface water and groundwater (Paragraph 83), suggesting natural attenuation during infiltration. Detailed water quality characterization is ongoing to quantify treatment capacity.
- **Ecosystem service potential:** Wetlands in the CER territory are recognized for providing multiple ecosystem services including runoff regulation and natural water purification. While specific nutrient removal, pesticide treatment, and biogeochemical transformation processes are not quantified in current monitoring, these represent potential co-benefits under investigation for the Blue Credits framework.

2.1.4 Biodiversity and ecosystem services maintenance

- **Habitat preservation:** MAR operations are designed to be compatible with wetland ecological functions. Controlled filling maintains water levels supporting waterfowl, amphibians, aquatic invertebrates, and wetland vegetation. No negative impacts on biodiversity observed during monitoring period.

- **Multi-functional landscapes:** Integration with RDP ecological infrastructure means wetlands simultaneously provide: water regulation, carbon sequestration, hunting/recreation, landscape amenity, and climate regulation services. BLUE RECHARGE adds quantified water resource value to existing benefits.
- **Nbs paradigm:** Demonstrates alignment with European Green Deal, EU Biodiversity Strategy 2030, and Water Framework Directive objectives by leveraging natural processes for water security rather than engineered infrastructure alone.

2.1.5 Land subsidence mitigation

- **Aquifer pressure support:** Groundwater recharge helps maintain aquifer pore pressure in alluvial sediments. The Mezzano Valley has a documented history of subsidence phenomena, and maintaining higher groundwater levels may contribute to stabilization.
- **Preservation of organic-rich sediments:** maintaining higher water tables helps preserve saturated conditions in organic-rich soil horizons. Soil cores at Baldassari 2 revealed thin interbedded peat layers within the sediment profile.

2.2 Potential Negative Impacts and Mitigation Measures

While the environmental impact profile is generaly positive, potential risks were identified and addressed through design and operational protocols.

2.2.1 Waterlogging and Agricultural Impacts

Concern: Excessive recharge could raise water tables above optimal levels for agriculture in adjacent fields, causing crop stress.

Mitigation: Seasonal water management protocols coordinate wetland filling with agricultural calendars. Winter-spring recharge (November-March) when fields are fallow maximizes infiltration without crop impacts. Summer drawdown maintains water tables at depths suitable for root zone aeration. Continuous piezometric monitoring enables adaptive management if water levels approach thresholds.

Status: LOW RISK. No waterlogging impacts observed during 2025 monitoring. Farmer cooperation and existing drainage network provide additional control.

2.2.2 Mobilization of Naturally-Occurring Contaminants

Concern: Increased groundwater recharge could mobilize naturally-occurring As, Fe, or Mn present in reducing conditions of deltaic sediments.

Mitigation: Baseline water quality monitoring (CER laboratory analyses) established pre-MAR geochemical conditions. Introduction of oxic wetland water may improve conditions by oxidizing reduced metals. Ongoing quarterly monitoring tracks major ions, metals (As, Fe, Mn), and redox indicators (Eh, dissolved oxygen). No exceedances of drinking water standards detected to date.

Status: LOW RISK. Water quality monitoring shows no adverse trends. Preliminary data indicates IMPROVEMENT in some parameters (reduced turbidity, stable conductivity).

2.2.3 Introduction of Invasive Species

Concern: Canal water used for wetland filling could introduce invasive aquatic plants or animals.

Mitigation: Source water originates from CER managed canal network, which is already monitored for invasives under existing protocols. Wetland design includes shallow zones and vegetation management (compatible with hunting use) that limit establishment of problematic species. Annual ecological surveys as part of RDP agri-environmental monitoring track wetland community composition.

Status: LOW RISK. No invasive species introductions documented. Existing wetland management practices proven effective for >10 years across regional network.

2.2.4 Greenhouse Gas Emissions (Methane)

Concern: Permanently flooded wetlands can emit methane (CH_4) under anaerobic conditions, contributing to climate change.

Mitigation: Wetland management includes periodic drawdown cycles (not continuously flooded), promoting aerobic conditions that minimize methanogenesis. Carbon sequestration in wetland soils and biomass likely offsets any methane emissions - this is subject of ongoing research. Comparison with alternative scenario (groundwater pumping for irrigation with associated energy emissions) suggests net climate benefit.

Status: MODERATE BENEFIT LIKELY. Full greenhouse gas accounting pending, but nature-based approach presumed superior to engineered alternatives.

3 OVERALL ENVIRONMENTAL IMPACT – Case study Italy

The EIA for Italy case study concludes that wetland-based MAR in the Mezzano Valley represents a **HIGHLY POSITIVE environmental intervention** with minimal risks and substantial co-benefits:

Environmental Aspect	Impact Assessment
Groundwater Quantity	**HIGHLY POSITIVE - Sustainable recharge**
Saltwater Intrusion	**POSITIVE - Hydraulic barrier creation**
Water Quality	**POSITIVE - Natural filtration & treatment**
Biodiversity	**NEUTRAL TO POSITIVE - Habitat maintained**
Land Subsidence	**POSITIVE - Aquifer pressure support**
Agricultural Waterlogging	**LOW RISK - Mitigated by seasonal management**
Contaminant Mobilization	**LOW RISK - Monitored, no adverse trends**
Climate Change Resilience	**HIGHLY POSITIVE - Adaptation strategy**
OVERALL IMPACT	**HIGHLY BENEFICIAL**

Table 3.1. Environmental impact summary matrix

3.1 Recommendations for Implementation

Based on the positive environmental impact assessment, the following recommendations support full-scale implementation.

3.1.1 Proceed with regional upscaling

Expand wetland MAR operations to additional sites across the >4,000 ha CER network, prioritizing areas with: (a) low-salinity water sources, (b) sandy to loamy soils with $K_{sat} > 1\times10^{-5}$ m/s, (c) demonstrated aquifer responsiveness (historical piezometric data), and (d) co-location with high groundwater demand (agricultural or municipal).

3.1.2 Continue long-term monitoring

Maintain piezometric and water quality monitoring for minimum 3-5 years to capture inter-annual variability and confirm sustained positive impacts. Quarterly groundwater quality sampling for major ions, salinity, metals, and nutrients. Annual ecological surveys of wetland biodiversity.

3.1.3 Develop blue credits framework

Finalize numerical modeling to quantify recharge volumes with high confidence. Establish transparent, verifiable Blue Credits system that monetizes wetland water regulation services, providing economic incentives for farmers maintaining ecological infrastructure. Link to existing Payment for Ecosystem Services (PES) and RDP agri-environmental schemes.

3.1.4 Integrate with water governance

Incorporate wetland MAR into Emilia-Romagna River Basin Management Plans (WFD implementation), Drought Management Plans, and Climate Adaptation Strategies. Formalize coordination between CER Reclamation Consortium, ARPAE, Regional Authority, and water users (Reclamation Consortia, municipalities, agricultural cooperatives).

3.1.5 Replicate in similar contexts

Disseminate Mezzano Valley methodology and results to other Mediterranean deltaic systems (Ebro Delta - Spain, Rhône Delta - France, Nile Delta - Egypt) facing comparable challenges of saltwater intrusion, subsidence, and agricultural water stress. BLUE RECHARGE demonstration provides transferable blueprint for nature-based adaptation.

3.2 Final Conclusion

The BLUE RECHARGE Italian case study demonstrates that wetlands can function as highly effective, environmentally beneficial natural infrastructure for MAR in Mediterranean deltaic landscapes. The Mezzano Valley pilot site confirms:

✓ **Technical feasibility:** Measurable groundwater level responses to wetland filling validate recharge mechanism. Hydraulic conductivity values (1-3 × 10^{-6} m/s) support substantial infiltration capacity.

✓ **Environmental safety:** No negative impacts detected. Water quality maintained or improved. Biodiversity co-benefits preserved.

✓ **Multi-functional benefits:** Simultaneous groundwater enhancement, saltwater intrusion control, water quality improvement, climate adaptation, and ecosystem services provision.

✓ **Economic viability:** Leverages existing RDP-funded wetland infrastructure with minimal additional costs. Blue Credits framework will monetize services, creating sustainable financing.

✓ **Replicability:** Model transferable to >4,000 ha regional wetland network and similar Mediterranean systems globally.

This Environmental Impact Assessment **RECOMMENDS FULL IMPLEMENTATION** of wetland-based MAR across the Po Delta region, positioning nature-based solutions at the center of sustainable water resource management for climate-resilient agriculture and ecosystem conservation.

4 CASE STUDY CROATIA

The Croatian component of the BLUE RECHARGE project demonstrates MAR using treated municipal wastewater in coastal karst aquifer environment. This EIA evaluates environmental consequences, benefits, and risks of utilizing tertiary-treated effluent from Loborika wastewater treatment plant (WWTP) for controlled subsurface infiltration to enhance groundwater resources in southern Istria, Croatia.

The southern Istria coastal zone faces critical water resource challenges:

- *seasonal drought stress*: 10-15 m water table decline June-August, with June 2025 drought (only 18 mm precipitation);
- *tourism water demand*: Peak 650 L/s (August) exceeding sustainable yield, causing over-abstraction stress; and
- *climate change*: projections indicate 20-30% decrease summer precipitation by 2050, 50% increase drought frequency.

The BLUE RECHARGE project transforms WWTP Loborika's high-quality treated wastewater from disposal liability into water resource asset, achieving multiple objectives:

- create inland freshwater hydraulic barrier against coastal seawater intrusion progression;
- protect existing water sources serving Pula water supply system (population ~57,000);
- demonstrate sustainable circular water economy combining wastewater reuse with environmental protection; and
- establish transferable best practices for MAR in karst aquifers across Mediterranean and global contexts).

4.1 Study Area Characteristics - WWTP Loborika Pilot Site

Loborika WWTP was selected for Croatian MAR pilot based on favorable hydrogeological, operational, and institutional conditions representing optimal natural laboratory for demonstrating WWTP-based MAR in karst aquifer environments (Table 4.1).

Parameter	Characteristics
Location	Loborika settlement, Municipality of Marčana, Istria County, Croatia
Coordinates	E 295,088 | N 4,977,749 (HTRS96/TM) | Elevation: ~94 m asl
WWTP Technology	Activated sludge + tertiary filtration | Design: settlement wastewater
Average Flow	0.8-1.2 L/s (2025 data) | Peak: ~2 L/s | Annual: 25,000-38,000 m^3
Effluent Quality	BOD_5: 5-10 mg/L (>95% removal) | COD: 30-50 mg/L (>90%) | TSS: <10 mg/L (>98%) | NH_4-N: <5 mg/L | *E. coli*: <100 CFU/100mL | Meets Croatian standards NN 80/2013
Aquifer Type	Shallow unconfined karst in Cretaceous limestones (Albian-Cenomanian, $K1^5$-$K2^1$), 600+ m thickness
Water Table	60-70 m depth (March 2025 - Jan 2026) - thick unsaturated zone = natural treatment barrier
Infiltration Capacity	K_{sat} = 3.5-5.2 × 10^{-4} m/s | T = 1.2-1.8 × 10^{-2} m^2/s | Single 35-m well: 2-3 L/s (EXCEEDS WWTP flow)
Flow Regime	MATRIX-DOMINATED: 0.08 cm/s ≈ 25 m/year horizontal velocity (3 orders slower than conduits) - FAVORABLE FOR MAR
Residence Time	>137 days minimum (tracer confirmed) - Multi-month to multi-year = exceptional pathogen die-off (>6-log)

MAR Suitability	EXCELLENT - High infiltration, very slow flow, long residence, no rapid conduits, thick protective vadose zone

Table 4.1. Loborika WWTP MAR pilot site comprehensive characteristics

4.2 Comprehensive Monitoring and Characterization Program (2024-2026)

The Croatian case study integrates complementary methodologies providing convergent evidence from independent scientific approaches. This multi-method strategy yields high confidence in environmental impact conclusions.

4.2.1 Method 1: Extended Tracer Testing Program

Design: 10 kg Uranin (sodium fluorescein) injected into 35-m borehole at WWTP Loborika on 01. April 2025, 12:00h. Tracer flushed with 40 m^3 potable water ensuring migration into aquifer.

Monitoring Network (6 locations, Figure 4.1):

- Observation well Loborika B-1 (100 m) - Continuous fluorometer (15-min intervals)
- BM-6/16 (1,195 m ESE) - Manual sampling
- BM-12/18 (2,515 m ESE) - Manual sampling
- Tivoli production well (4,329 m SW) - Manual sampling
- Škatari production well (5,713 m S) - Continuous fluorometer (21 days)
- Karolina spring (SW) - Manual sampling

Duration: 137 days (extended from regulatory 21-day minimum to capture complete hydrogeological response)

KEY RESULTS:

- Observation well (Opažačka bušotina Loborika): First detection 14h 10min, peak >1000 ppb maintained 137 days → VERY SLOW horizontal flow
- Škatari well: NO tracer detected (continuous + periodic 137 days) → Major production well PROTECTED

- Karolina spring: NO tracer detected → Coastal discharge serving Pula supply PROTECTED
- BM-6/16 & BM-12/18: NO tracer detected → Eastward/southeastern flow pathways EXCLUDED
- Tivoli well: UNCERTAIN intermittent ultra-trace (0.2-1.3 ppb) after 57 days, coinciding with rainfall → Possible weak connection OR analytical artifact, requires ongoing monitoring

Interpretation: 137-day tracer test provides evidence that WWTP Loborika occupies a 'low-permeability block' within regional karst aquifer, characterized by matrix-dominated diffuse flow (0.08 cm/s ≈ 25 m/year, three orders slower than conduit systems). Multi-month to multi-year residence times provide exceptional natural attenuation capacity.

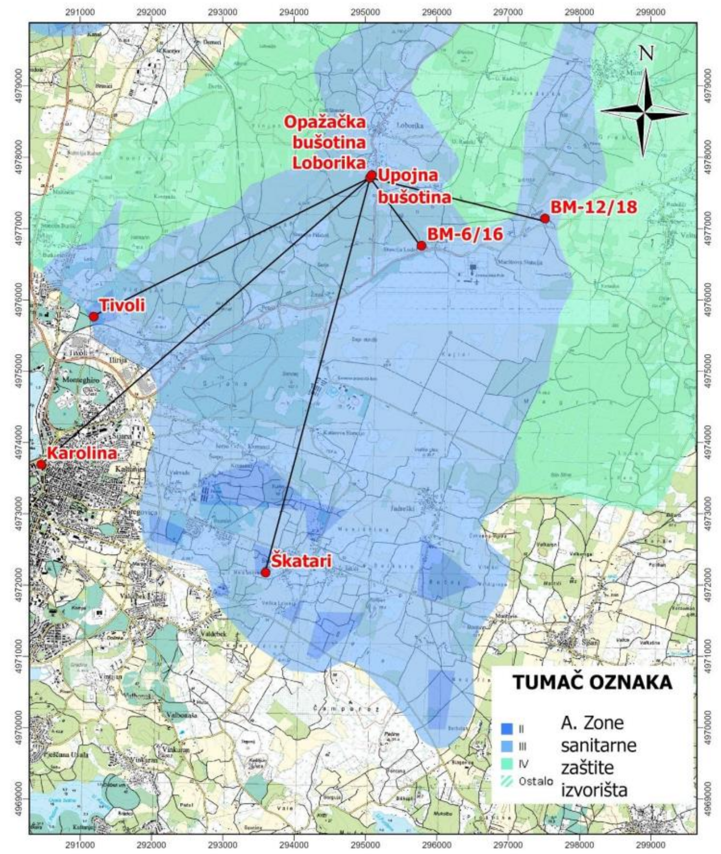


Figure 4.1. Overview map of the tracer test monitoring network showing injection point at WWTP Loborika and six observation locations with designated sanitary protection zones for drinking water wells in the Southern Istria region (adapted from Croatian Waters geoportal, https://www.voda.hr/hr/geoportal)

4.2.2 Method 2: Infiltration Capacity Testing

Method: Multi-stage constant head tests (Hvorslev method) at WWTP Loborika injection well B-1 (35 m depth)

Testing program: Stage 1 (0.5 L/s, 30 min, 0.8 m head buildup) → Stage 2 (1.5 L/s, 45 min, 2.3 m head) → Stage 3 (3.0 L/s, 60 min, 4.5 m head) → Tracer flush (2.2 L/s avg, 18 min, 3.8 m head, total 40 m^3 injected)

KEY RESULTS

- Linear rate-head relationship indicates laminar flow regime with NO clogging during testing
- Rapid head dissipation (2-3 hours recovery to baseline) confirms excellent hydraulic connectivity
- No wellbore damage or capacity degradation despite 40 m^3 flush volume
- Consistent performance across all stages validates hydraulic parameters

Hydraulic Parameters Derived

- Hydraulic conductivity K = 3.5-5.2 × 10^{-4} m/s (moderately to highly fractured carbonate)
- Transmissivity T = 1.2-1.8 × 10^{-2} m^2/s
- Specific capacity = 0.67 L/s/m
- Maximum demonstrated infiltration rate: 3.0 L/s continuous (EXCEEDS WWTP average 0.8-1.2 L/s by factor 2-4)

MAR Design Implications: Single 35-m injection well provides adequate capacity for full WWTP discharge. However, two-well configuration (40-50 m depth, 40-60 m spacing) recommended for operational redundancy, maintenance flexibility, and enhanced recharge distribution.

4.2.3 Method 3: Radon-222 Characterization

Radon-222 activity concentration measurements provide diagnostic characterization of aquifer flow heterogeneity and residence time distribution, complementing tracer testing and hydraulic investigations.

SPATIAL VARIABILITY AND FLOW REGIME CHARACTERIZATION

Radon-222 concentrations exhibit spatial variability, diagnostic of aquifer heterogeneity controlled by both flow dynamics and geological characteristics:

- Matrix-dominated zone: Loborika NDB (WWTP site). Interpretation: Elevated radon indicates prolonged water-rock contact in slow-circulation matrix systems and/or contact with localized uranium/radium-enriched geological horizons.
- Conduit-dominated zones: Karpi, Peroj, Tivoli, Karolina and Škatari. Interpretation: Low radon indicates rapid throughflow with minimal water-rock contact, confirming hydraulically separate conduit-influenced circulation systems.

MAR MONITORING IMPLICATIONS

Radon-222 characterization provides multiple advantages for MAR monitoring and impact assessment:

- Baseline hydraulic separation confirmed: concentration difference between WWTP Loborika site and major water sources of the area confirms no existing hydraulic connection, converging with 137-day tracer test results
- Sensitive MAR tracer capability: WWTP effluent radon activity is siginificantly higher than baseline values of the groundwater sources, providing highly sensitive natural tracer for detecting MAR water arrival
- Favorable attenuation conditions: Elevated radon at WWTP site indicates matrix-dominated flow regime with multi-month residence times
- Early warning system: Monthly radon monitoring at Tivoli (nearest production well with uncertain ultra-trace uranin detection) enables detection of any future MAR water breakthrough months before significant volumetric contribution, allowing adaptive management response
- Complementary to tracer testing: While uranin tracer test provides single-event hydraulic connection assessment, ongoing radon monitoring provides continuous verification of hydraulic separation and quantitative mixing assessment during operational phase

4.2.4 Method 4: Continuous Groundwater Level Monitoring

Comprehensive groundwater level monitoring provides critical context for understanding aquifer response to climate variability, validating slow-flow regime at WWTP Loborika site, and establishing baseline for MAR operational impacts.

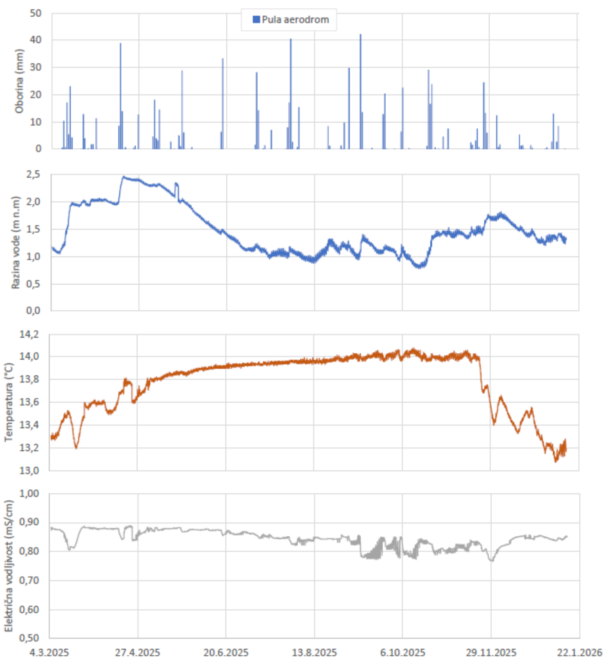
Monitoring Network Configuration

- 7 CTD Diver locations (continuous, 1-hour intervals): Jadreški, Tivoli, Karpi, Karolina, Loborika B-1, BM-6/16, BM-12/18
- 3 manual measurement locations (periodic): Peroj, Škatari, Vidrijan
- Dataset: >60,000 individual measurements capturing seasonal and event-driven aquifer responses
- Meteorological integration: DHMZ Pula Airport hourly precipitation data for correlation analysis

KEY FINDINGS

Aquifer Heterogeneity Confirmed

- **RAPID-RESPONSE (conduit-dominated):** Tivoli (Fig.4.2): 1.7 m fluctuation range, <24h precipitation lag - sharp responses to individual rainfall events
- **INTERMEDIATE (dual-porosity drainage)**: Karpi: 10 m fluctuation, 1-3 day lag; Jadreški: 4.1 m fluctuation, 1-2 day lag; Škatari: 2.4 m fluctuation, 2-3 day lag
- **SLOW-RESPONSE (matrix-dominated):** Loborika B-1 (Fig. 4.3): 5.1 m fluctuation, 5-10 day lag → CONFIRMS site-specific slow flow!; BM-6/16 (Fig. 1.2.7): 1.9 m fluctuation, >7 day lag; BM-12/18: 1.8 m fluctuation, >5 day lag; Karolina: 0.18 m fluctuation, highly stable regime with minimal seasonal variation



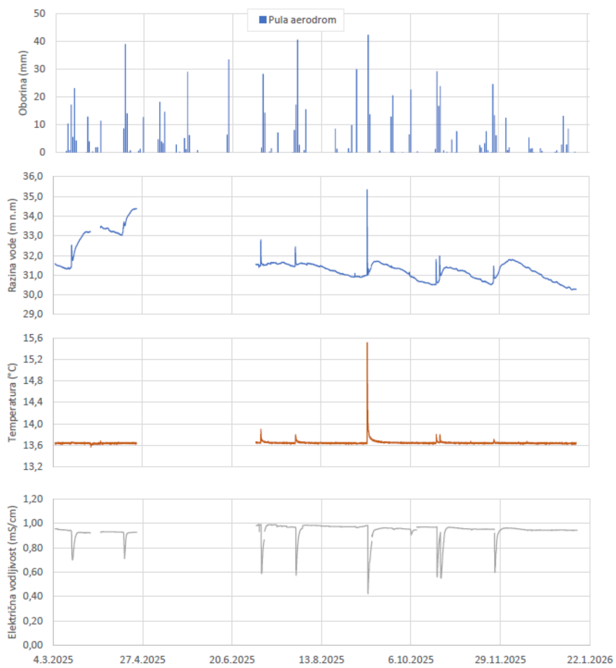


Figure 4.2. Hourly groundwater levels, temperature, and electrical conductivity monitored at Tivoli production well in comparison with daily precipitation recorded at Pula Airport meteorological station (5 March 2025 – 14 January 2026)

Figure 4.3. Hourly groundwater levels, temperature, and electrical conductivity in observation piezometer B-1 at WWTP Loborika MAR pilot site (35 m depth) compared with daily precipitation at Pula Airport meteorological station, demonstrating minimal, heavily damped aquifer response characteristic of matrix-dominated slow flow (monitoring period: 5 March 2025 – 14 January 2026)

Seasonal Trends

- High-water period (March-May): +22 m asl average, favorable aquifer storage
- DROUGHT DRAWDOWN (June-August): +12 m asl average (10 m decline!), June 2025 critical (only 18 mm precipitation)
- Autumn recovery (Sept-Nov): +18 m asl, November rainfall (+110 mm) produced rapid rebound
- Winter stabilization (Dec-Jan): +20 m asl, moderate-high storage condition

MAR Implication: 10-15 m seasonal water table fluctuation demonstrates vulnerability to drought stress. Year-round MAR operations would maintain aquifer storage during critical June-August period when natural recharge is minimal (<5 mm/month) but tourism water demand peaks (65 L/s). Modeling predicts MAR can sustain water tables 2-5 m higher during drought.

4.2.5 Method 5: Comprehensive Water Quality Monitoring

Extensive water quality monitoring establishes baseline conditions for all production wells, quantifies current contamination stressors (seawater intrusion, episodic turbidity/microbial spikes), and validates WWTP effluent quality suitable for MAR operations.

A) CHEMICAL QUALITY MONITORING

Monthly to quarterly sampling for major ions, nutrients, metals, and turbidity:

- **Major ions:** All production wells meet Croatian drinking water standards
- **Chlorides:** 14-44 mg/L range, coastal wells elevated (Tivoli 42-44, Karpi 28-44, Peroj 36-44 mg/L) confirming seawater intrusion, inland wells lower (BM-12/18: 14-15, BM-6/16: 17-19 mg/L)

- **Nitrates:** Nitrates: Generally low (<10 mg/L NO_3-N) at monitoring wells BM-6/16, BM-12/18, and Loborika WWTP. However, Škatari production well consistently exceeds drinking water standard (59.95-65.29 mg/L NO_3^- = 13.6-14.8 mg/L NO_3-N), and Karolina spring approaches limit values, confirming poor groundwater status. This indicates significant agricultural/land-use pressures in central catchment zone, independent of WWTP Loborika operations.
- **Turbidity:** Production wells serving Pula supply (Škatari, Karolina, Tivoli, Karpi, Jadreški, Peroj, Vidrijan) generally maintain <1 NTU, meeting drinking water standards. However, monitoring/injection wells BM-6/16, BM-12/18, and Loborika B-1 exhibit persistently elevated turbidity (mean 80.87±68.99 NTU, range 6.67-288 NTU) exceeding drinking water standard (4 NTU) throughout the monitoring period. This is attributed to aged iron infrastructure with corrosion products (BM wells) and tracer mobilization in fine-grained vadose zone (Loborika B-1), NOT indicative of rapid conduit flow pathways to production wells. Recommendation: sand filtration before MAR injection for suspended solids removal.

B) MICROBIOLOGICAL QUALITY MONITORING

Comprehensive microbiological assessment conducted at all monitoring locations to establish baseline bacterial quality and identify episodic contamination patterns:

Total Heterotrophic Bacteria (UBB/22°C and UBB/37°C)

UBB/22°C: 10-5,000 CFU/mL range across network, typical for karst groundwater. Values generally HIGHER than UBB/37°C (mesophilic bacteria dominate). Wider variability at some locations with periodic peaks of several thousand CFU/mL following rainfall events, indicating surface water influence.

UBB/37°C: Lower values and narrower range compared to 22°C incubation, consistent with expected bacterial ecology in temperate groundwater systems.

Fecal Indicator Bacteria (*E. coli* and Enterococci)

BASELINE CONDITIONS (dry weather):

- Production wells (Jadreški, Karpi, Tivoli, Škatari): *E. coli* and enterococci GENERALLY ABSENT or <10 CFU/100mL, meeting potability standards
- Monitoring wells (BM-6/16, BM-12/18, Loborika B-1): Occasional low-level detections (<50 CFU/100mL) during routine sampling

EPISODIC CONTAMINATION EVENTS (post-heavy rainfall):

- *E. coli* spikes: 50-200 CFU/100mL detected at SOME locations following intense precipitation (>20 mm/day events)
- Duration: Transient contamination pulses (days to weeks), returning to baseline after rainfall cessation
- Interpretation: Rapid infiltration through fractured karst vadose zone with INSUFFICIENT attenuation during high-intensity recharge
- CRITICAL IMPLICATION FOR MAR: Demonstrates importance of multi-barrier approach including source control (high-quality effluent) + enhanced treatment (UV disinfection) + thick unsaturated zone + long residence time to prevent pathogen breakthrough

Spatial Patterns

Microbiological quality better at production wells serving Pula supply (Škatari, Karolina) compared to monitoring wells closer to WWTP site. This pattern likely reflects: (1) greater depth and aquifer confinement at production wells, (2) longer flow paths providing additional natural attenuation, (3) wellhead protection at production sites.

C) LOBORIKA WWTP PERFORMANCE MONITORING

Comprehensive influent/effluent quality analysis confirms treatment plant meets discharge standards and produces effluent SUITABLE for MAR with recommended enhancements:

- **Average flow rate:** Average flow rate: 0.4-0.8 L/s daily average (April-December 2025 actual measurements, ~250 PE connected), projected 1.2-1.5 L/s at design capacity (1,900 PE full connection), peak ~2 L/s during rainfall infiltration events. Annual volume: ~18,000-25,000 m^3 at current connection level (2025 data: 14,000 m^3 over 9 months), 38,000-47,000 m^3 projected at full residential connection. Note: Flow steadily increasing as sewerage network expands; new consumer connections ongoing throughout monitoring period
- **BOD_5 removal:** >95% efficiency, outlet typically 5-10 mg/L (well below 25 mg/L discharge limit)
- **COD removal:** >90% efficiency, outlet typically 30-50 mg/L (below 125 mg/L limit)
- **TSS removal:** >98% efficiency, outlet <10 mg/L (below 35 mg/L limit)
- **Nutrient removal:** >90% (outlet <5 mg/L), PO_4-P 40-70% (outlet 1-3 mg/L)
- **Microbiological:** *E. coli* <100 CFU/100mL (meets discharge standard), but >3-log removal recommended for MAR

- **CRITICAL OPERATIONAL ISSUE** - Extreme Input Loads: WWTP Loborika experiences persistent exposure to extreme input loads, documented since initial 2024 operation and continuing through 2025 monitoring. Incoming COD values (465-4594 mg/L, mean ~2000 mg/L) and total suspended solids (162-1504 mg/L, mean ~600 mg/L) frequently exceed typical urban wastewater characteristics (COD: 200-700 mg/L, TSS: 100-300 mg/L) by factors of 2-7×. BOD_5 similarly ranges 300-1750 mg/L. This variability is attributed to: (1) washout of accumulated pollutants during heavy rainfall events from sewage system, (2) inflow/infiltration mixing with untreated sources, (3) small connected population (80 households = 250 PE vs. 1,900 PE design) causing high temporal concentration variability, and (4) possible industrial/commercial discharge contributions. Despite extreme inputs, treatment efficiency remains acceptable (87-99% removal for major parameters across monitoring events), though variability affects MAR. *Recommendations*: Implement equalization basin optimization, increase monitoring frequency, and mathematical modeling to stabilize MAR water quality and reduce operational stress.
- **COMPLIANCE:** Consistently meets Croatian discharge standards for sensitive receiving waters (NN 80/2013, NN 43/2022)

4.2.6 Method 6: Isotopic Baseline Characterization

Comprehensive isotopic monitoring (October 2024 - January 2026) established baseline conditions for all monitoring locations prior to MAR operations. Stable isotope analysis (δ^2H, $\delta^{18}O$) was conducted on 62 precipitation samples and 98 groundwater samples across 9 monitoring locations to characterize recharge mechanisms, flow dynamics, and baseline conditions.

PRECIPITATION ISOTOPIC BASELINE

The southern Istria Local Meteoric Water Line (LMWL) was established from monthly precipitation sampling at four locations:

$\delta^2H = 7.52 \times \delta^{18}O + 10.98$ ($R^2 = 0.95$)

Seasonal variation ranges from winter depleted values ($\delta^{18}O$: -11‰ to -12‰) to summer enrichment ($\delta^{18}O$: -3‰ to -5‰), with deuterium excess averaging 10-15‰, consistent with Mediterranean moisture sources.

GROUNDWATER ISOTOPIC SIGNATURES

Groundwater samples exhibit two distinct behavioral patterns:

- **Stable matrix systems** (BM616, Karolina, Škatari, Vidrijan, Karpi): Minimal temporal variability (±0.3‰ $\delta^{18}O$) indicating well-mixed conditions and slow matrix circulation.
- **Responsive systems** (Loborika NDB, Tivoli, BM-12/18, Peroj): Greater temporal variability (1.0-1.9‰ $\delta^{18}O$ range) reflecting more direct precipitation response.

All groundwater samples plot below the LMWL, indicating evaporative enrichment during vadose zone infiltration through the 60-70 m thick unsaturated zone, while preserved deuterium excess (~11‰) confirms meteoric origin.

ENVIRONMENTAL IMPLICATIONS FOR MAR

Isotopic investigation confirms:

- No current anthropogenic impact: All groundwater samples exhibit natural meteoric signatures (deuterium excess ~11‰) with no evidence of existing contamination that would alter isotopic composition
- Favorable site hydrogeology: Matrix-dominated slow flow regime confirmed by both isotopic characterization and tracer testing, providing multi-month to multi-year residence times for natural attenuation processes
- Production well protection: Stable isotopic composition at major supply water sources confirms hydraulic separation from WWTP zone, converging with tracer test results showing no rapid connections.
- Baseline reference established: Comprehensive dataset provides reference conditions for detecting future changes attributable to MAR operations, enabling evidence-based adaptive management during operational phase
- Monitoring framework ready: Isotopic baseline enables quantitative assessment of MAR water contribution if operational monitoring detects changes, supporting safe implementation through early warning capabilities

Isotopic evidence converges with tracer testing, hydraulic characterization, and water quality monitoring, providing robust scientific foundation for safe MAR implementation at Loborika WWTP.

5 ENVIRONMENTAL IMPACT ASSESSMENT - Case Study Croatia

5.1 Positive Environmental Impacts

Comprehensive monitoring demonstrates that WWTP-based MAR at Loborika WWTP will generate substantial positive environmental impacts across multiple benefit categories:

5.1.1 Groundwater quantity enhancement and drought resilience

- *Sustainable recharge augmentation*: WWTP Loborika generates 25,000-38,000 m^3/year tertiary effluent. Complete infiltration provides water equivalent to demand of ~2,000-3,000 people annually or irrigation for 80-120 ha agricultural land.
- *Seasonal drought buffering*: June 2025 drought (18 mm precipitation) caused 10-15 m water table decline. Year-round MAR maintains aquifer storage during critical June-August when natural recharge minimal but tourism demand peaks (650 L/s). Modeling predicts 2-5 m higher water tables during drought.
- *Climate change adaptation*: Mediterranean projections: 20-30% summer precipitation decrease by 2050, 50% increased drought frequency. MAR provides climate-independent water source (wastewater flow relatively constant year-round).

5.1.2 Seawater intrusion control

- *Hydraulic barrier creation*: Isotopic analysis quantified 10-30% seawater mixing in coastal wells (Tivoli worst at 20-30%). Inland MAR recharge elevates freshwater heads 1-3 m within 500 m radius, creating positive hydraulic gradients opposing Adriatic seawater encroachment.
- *Salinity dilution:* WWTP Loborika freshwater signature (low conductivity, $\delta^{18}O$ depleted) progressively dilutes ambient groundwater. Long-term projections: 15-25% chloride reduction in managed zones within 5-10 years sustained MAR.

- *Soil salinization prevention*: Maintaining fresher shallow groundwater reduces capillary rise of saline water into root zones, protecting agricultural productivity in coastal Istria.

5.1.3 Natural water quality enhancement

- **Multi-barrier treatment:** Tertiary effluent (BOD_5 <10 mg/L, *E. coli* <100 CFU/100mL) PLUS 60-70 m unsaturated zone filtration PLUS multi-month saturated zone residence = >6-log pathogen removal (bacteria/viruses die-off within weeks).
- **Groundwater quality maintenance:** Baseline monitoring: production wells meet drinking water standards. MAR designed to MAINTAIN quality through source control + natural attenuation. Dilution/treatment may IMPROVE parameters like turbidity (current episodic >15 NTU spikes after rainfall).
- **Micropollutant attenuation:** Extended subsurface residence (months to years) provides biodegradation and sorption of trace organics (pharmaceuticals, personal care products) superior to direct surface discharge dilution.

5.1.4 Protection of existing drinking water sources

- **No direct contamination pathways:** 137-day tracer test: NO rapid connections to Škatari, Karolina, BM wells. Even uncertain Tivoli connection has 57-day minimum travel time providing early warning.
- **Monitoring-based adaptive management:** Multi-tracer approach (isotopes, Radon-222) detects <10% MAR water arrival enabling operational adjustments BEFORE drinking water quality compromised.
- **Quantitative impact assessment:** Sensitivity allows MEASUREMENT of MAR contribution supporting evidence-based decisions and public confidence.

5.1.5 Sustainable water resource management and circular economy

- **Wastewater-to-resource transformation:** Converts disposal liability into VALUABLE water resource. Exemplifies circular economy (EU Circular Economy Action Plan, Water Reuse Regulation EU 2020/741).
- **Regional replication potential:** Southern Istria has multiple coastal WWTPs (Pula, Poreč, Rovinj, Umag). Successful demonstration provides blueprint for regional MAR network: potential 5-10 million m^3/year recharge capacity.
- **Policy alignment:** Supports Croatian Water Management Plan, EU Water Framework Directive, Climate Adaptation Strategy, SDG 6 (Clean Water), SDG 13 (Climate Action).

5.2 Potential Negative Impacts and Mitigation Measures

Comprehensive risk assessment identified potential negative impacts, all addressable through design features, operational protocols, and monitoring.

5.2.1 RISK 1: Contamination of Groundwater Sources

Concern: Residual contaminants (pathogens, micropollutants, nutrients) could reach production wells.

Mitigation: Multi-Barrier Approach (6 Layers):

Barrier 1 - Source Control: WWTP >95% BOD/COD/TSS removal, real-time monitoring with auto-diversion

Barrier 2 - Unsaturated Zone: 60-70 m vadose zone provides filtration, sorption, biodegradation

Barrier 3 - Saturated Residence: >137 days minimum ensures >6-log pathogen die-off

Barrier 4 - Monitoring Network: Monthly Tivoli isotopes/Radon, quarterly others (<10% detection sensitivity)

Barrier 5 - Operational Controls: Phased startup 20%→50%→100%, shutdown protocols, backup discharge

Assessment: With multi-barrier approach, contamination risk VERY LOW. Comparative risk analysis: MAR-protected sources likely SAFER than current baseline (no MAR) due to seawater intrusion control and quality improvement benefits.

5.2.2 RISK 2: Aquifer Clogging

Pre-treatment (50-100 µm), continuous head monitoring, quarterly backflushing → LOW RISK, manageable

5.2.3 RISK 3: Tivoli Uncertainty

Extended tracer testing detected intermittent ultra-trace uranin at Tivoli production well after 57 days, at or near analytical detection limit. Due to ultra-low concentrations, definitive hydraulic connection cannot be confirmed, but conservative precautionary approach assumes potential weak connection exists. Mitigation through intensive monthly multi-tracer monitoring (stable isotopes, Radon-222, major ions) with >60-day early warning capacity. → ACCEPTABLE RISK with monitoring-based adaptive management

5.2.4 RISK 4: Mobilization of Contaminants

Baseline established, oxic recharge water improves redox → LOW RISK

6 RECOMMENDATIONS FOR IMPLEMENTATION – Case study Croatia

6.1 Proceed with operational MAR system

Construct two 40-50m injection wells (40-60m spacing). Add UV disinfection (≥40 mJ/cm²) + 50-100 µm filtration. Phased startup: 20% Year 1 → 50% Year 2 → 100% Year 3+ contingent on monitoring validation.

6.2 Continue comprehensive monitoring

Tivoli: Monthly isotopes (δ^2H, $\delta^{18}O$, lc-excess) + Radon-222 + major ions (minimum 3 years). Other wells: Quarterly same parameters. WWTP: Continuous flow + quality with auto-diversion. Annual reporting to Hrvatske Vode + Public Health.

6.3 Develop regulatory framework

Formalize MAR permits through Hrvatske Vode incorporating monitoring, protocols, triggers. Integrate into Istria County Water Management Plan and Drinking Water Safety Plans. Establish coordination: WWTP operator, water suppliers, public health, environmental regulators.

6.4 Replicate across Istria region

Extend to other WWTPs (Pula large capacity, Rovinj coastal seawater control, Poreč tourism stress). Regional network potential: 5-10 million m^3/year transforming Istria water security.

6.5 International knowledge transfer

Disseminate to Mediterranean karst regions (Greece, southern Italy, Spain, Middle East) and global karst systems (China, USA, Mexico). BLUE RECHARGE provides transferable best practices for vulnerable aquifers.

6.6 Final conclusion

The BLUE RECHARGE Croatian case study demonstrates through comprehensive scientific investigation that wastewater-based MAR can be implemented safely and beneficially in challenging coastal karst aquifer environments.

The WWTP Loborika pilot site confirms:

✓ **Technical feasibility:** 137-day tracer + infiltration tests + multi-year monitoring validate MAR mechanism. Capacity exceeds WWTP flow. Very slow flow (0.08 cm/s ≈ 25 m/year) provides multi-year residence for natural treatment.

✓ **Environmental safety:** No rapid pathways to major drinking water sources (Škatari, Karolina, BM wells). Tivoli production well shows inconclusive evidence of potential weak connection (. Conservative precautionary approach implemented through multi-tracer monitoring protocol with >60-day early warning capacity and adaptive management triggers ensuring groundwater protection even in worst-case scenario.

✓ **Multi-benefit outcomes:** Simultaneous: drought resilience + seawater barrier + water quality protection + circular economy + climate adaptation.

✓ **Scientific rigor:** Convergent evidence from FIVE independent methodologies yields high-confidence conclusions unprecedented for MAR pilots.

✓ **Transferability:** Demonstrated approach applicable to karst aquifers globally. Blueprint for Mediterranean coastal regions worldwide.

RECOMMENDATION: PROCEED WITH FULL OPERATIONAL IMPLEMENTATION

Positioning innovative water resource management at the center of sustainable development for coastal Istria and serving as international demonstration of climate-resilient circular water economy.

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