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Guidelines for water resource management approaches

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Guidelines for water resource management approaches

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A. Introduction

Different lines of action can be pursued to enhance urban water management, as demonstrated by the outcomes of the MAURICE project and synthesised in the holistic "Sponge city" approach. Nevertheless, following the Climate-ADAPT's framework for adaptation to climate change, priorities should be defined based on the specific climate risks and vulnerabilities of each urban area, and actions should be tailored to the local social, economic, and environmental context.

While guidelines for approaches prioritising rainwater and water quality management are provided in other project outputs (e.g., outputs O3.3, O3.4, O3.5), the present deliverable builds on the findings from the pilot actions in Milan and Stuttgart, which focused on groundwater quantity management in metropolitan settings. It is important to highlight that these and all MAURICE pilots were developed through continuous collaboration among stakeholders from local public administrations, water management authorities, and scientific and technical institutions.

The document presents:

i) **A framework to assess urban adaptation solutions enabling aquifer recharge**, based on the case of the City of Stuttgart-Feuerbach;

ii) **Guidelines for the implementation of Agricultural Managed Aquifer Recharge**, based on lessons learned from the pilot action in the metropolitan area of Milan.

Stuttgart-Feuerbach represents an urban area that is affected by a dramatic decline in groundwater levels during the last 10-15 years. Due to a very complex geology with varying hydrogeologic properties, mitigation measures need careful planning. Section B of this document outlines the planning process undertaken in this context, in which different urban adaptation options aimed at enhancing aquifer recharge were evaluated. The assessment relied on long-term groundwater monitoring data, field test data, and results from a numerical groundwater model for the pilot area, developed to understand the system's behavior. By means of this instrument, scenario simulations were performed to evaluate the effects of possible adaptation options on the groundwater levels.

Milan pilot action focuses instead on an agricultural area where future climate conditions may reduce water availability during the irrigation season. Leveraging the presence of a dense irrigation network, a tailored adaptation measure was tested over three consecutive winters: water was circulated through irrigation canals during winter and subsequently distributed across agricultural fields to promote infiltration and recharge the aquifer below. Section C of this report contains the lessons learned throughout the implementation of this pilot action and presents the resulting "MAURICE's guidelines for the implementation of Agricultural Managed Aquifer Recharge as a drought-adaptation measure".

B. Urban adaptation solutions enabling aquifer recharge

1. Overview of possible adaptation solutions

1.1. Unsealing of selected areas

Stuttgart-Feuerbach is a densely inhabited and industrialized urban district, where more than 70 % of the surface is sealed. This extensive sealing increases surface runoff and limits infiltration and groundwater recharge.

By using existing gaps or by redeveloping areas after demolition of buildings, small spaces of blue-green infrastructure could be implemented, enhancing not only groundwater recharge but also increasing the overall quality of living. In addition, remodeling parking areas by installing semi-permeable surfaces, such as grass paving blocks, can contribute to higher infiltration rates and support the restoration of groundwater levels.

1.2. Targeted Infiltration of Roof Water and Surface Runoff

In the context of site development or new building constructions, facilities to collect roof water and road runoff can be integrated with targeted infiltration systems, such as infiltration ditches, drain trenches, etc., to support local aquifer recharge.

Before implementing such measures, infiltration capacities at each location must be assessed, as the permeability of near-surface strata varies considerably across the district. However, even small infiltration volumes can improve moisture of soil, support vegetation growth, thus improving urban climatic conditions.

Careful planning remains essential to avoid unintended consequences, particularly the risk of basement flooding during heavy rainfall events, which may occur where the water holding capacity of near-surface soils is limited.

1.3. Construction and Operation of Infiltration Wells

The construction of infiltration wells in suitable urban areas, targeting permeable subsurface layers with a higher intake capacity, allows for a more efficient input of water into the aquifer. In contrast to infiltration by trenches, these systems can convey significant larger volumes directly to deeper, more conductive strata, thereby enhancing the recharge of underground groundwater resources.

By directing infiltration to selected permeable depths, the risk of flooding basements can be substantially reduced. However, considerable amounts of water would have to be collected and transported to the input areas to achieve relevant effects, as described below in Section B – Chapter 3.

1.4. Reduction of Groundwater Extractions

As stated above, a dramatic decline of groundwater levels could be observed in the Feuerbach area during the last decades. Consequently, the amount of water extracted by wells also went down dramatically. Since 2010, extraction rates declined from approximately 8 l/s to approximately 2,5 l/s. Figure 1 gives an impression.

The remaining groundwater resources are urgently needed for industrial and domestic purposes and running groundwater remediation measures. However, it is extremely necessary to avoid further water losses, for example by preventing groundwater drawdowns for building construction by appropriate measures. In other cases, options should be evaluated to give the water back to the groundwater aquifer by rein filtration. A discharge to sewage should be avoided in any case. When planning groundwater remediation measures, options to avoid large volume groundwater extractions should be checked and evaluated. In other cases, options should be evaluated to give the water back to the groundwater aquifer by rain filtration. A discharge to sewage should be avoided in any case.

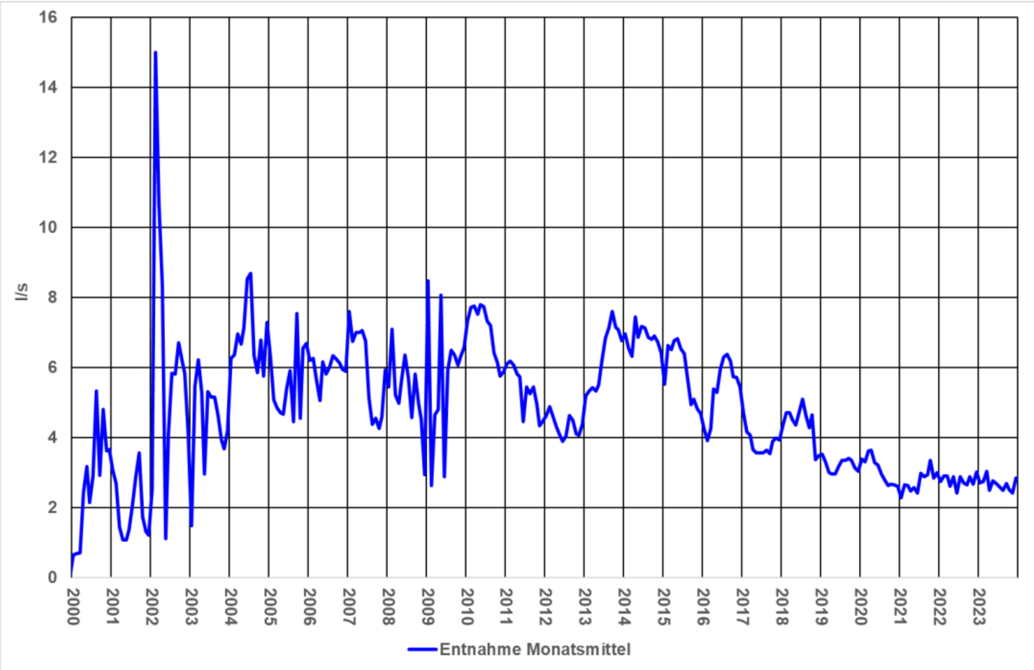


Figure 1: Development of groundwater withdrawals in the pilot area in since 2000

2. Evaluation of possible adaptation solutions

To identify the most effective adaptation option, an assessment of their quantitative influence on the overall groundwater resources is required. For this purpose, the use of decision-support tools is recommended. For the Stuttgart-Feuerbach area, a numerical groundwater flow model was developed and evaluated using groundwater monitoring data and field test results.

Using this model, the influence of the first three water input scenarios listed above was analyzed and evaluated. The last option, "Reduction of Groundwater Extractions", could not be assessed, as no reliable data about potential water saving amounts are available.

For a more comprehensive assessment of the adaptation solutions, future climate projections were considered in the framework. Regional climate prognosis models for the upcoming period 2036–2065 indicate that groundwater recharge in the area is estimated to decline by 25% to 50%, compared to the period 1991–2020. This translates into an additional input, between 12 and 20 l/s, necessary to compensate for this deficit and reverse the current trend of sinking groundwater levels. Such input was considered in the calculations of the numeric groundwater model.

2.1. Increase of Groundwater Recharge by unsealing measures

Groundwater recharge in unsealed areas of Stuttgart-Feuerbach has been estimated at 200 mm/y. This corresponds to a recharge rate of 6.3 l/s per km². Each additional square kilometer of unsealed surface can therefore generate additional 6.3 l/s of water input, thus providing a significant contribution toward compensating the existing groundwater deficit.

2.2. Groundwater infiltration via the ground surface

The numerical model was used to test effects of surface infiltration through infiltration trenches. In this case, 2.5 l/s of water were continuously infiltrated to the upper quaternary aquifer in the northern part of the district (see Figure 2). Figure 3 shows the effects in the aquifer after one year of continuous infiltration.

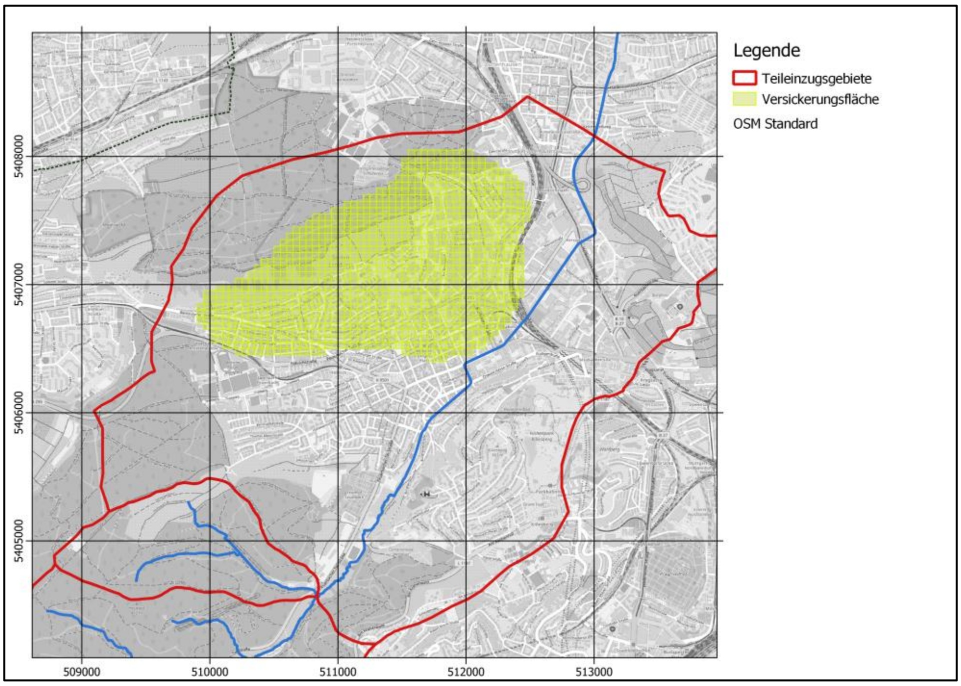


Figure 2. Area of assumed infiltration in the groundwater model

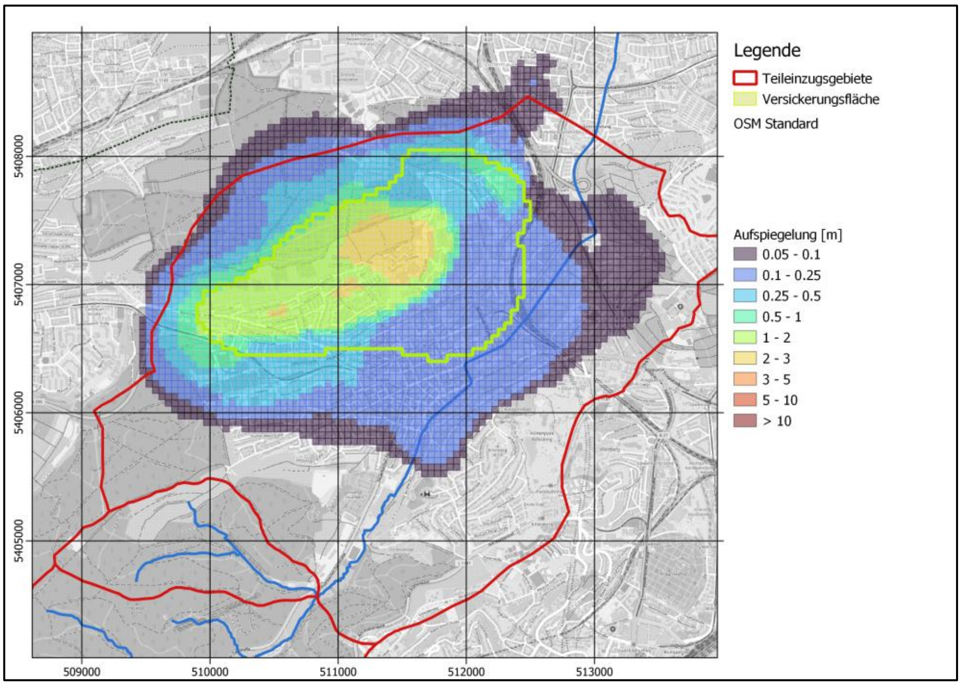


Figure 3: Groundwater elevations in quaternary aquifer after one year of infiltration

Model results show that the influence of water addition extends well beyond the boundaries of the infiltration area. However, the resulting rise in groundwater levels is rather modest, with a maximum increase of 3m in the central portion of the infiltration area.

In some low permeability areas, groundwater levels would locally rise above ground surface after one year of continuous infiltration. This represents a serious risk, as basement flooding should be avoided in any case.

The effects are rather limited in deeper groundwater storeys, with a maximum rise of 0.5 m (see Figure 4, example Bochinger Horizont).

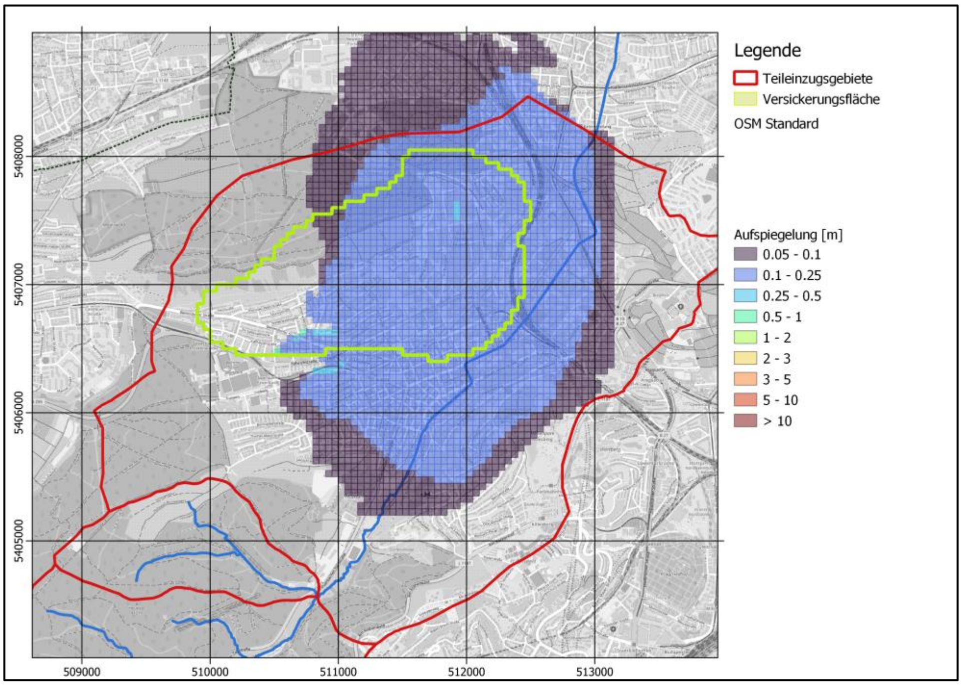


Figure 4: Calculated Rise of the Groundwater table after Infiltration of 2.5 l/s for 6 months in Quarternary, Rise in Bochinger Horizont.

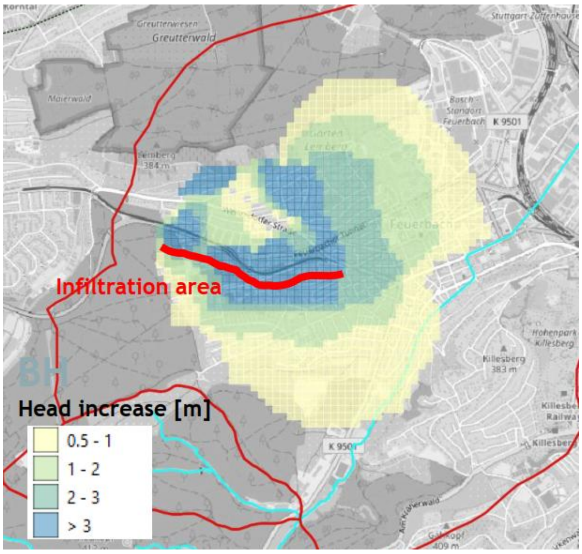
2.3. Groundwater infiltration via wells

The numeric groundwater model examined the theoretical effect of a targeted infiltration via wells, tapped in selected aquifers, in different city districts. Local well infiltration was simulated for different layers of the shallow aquifer system.

Infiltration runs were implemented: in the western part of the central city district, west of city center, south of city center, near Feuerbach creek, and in the western periphery, between Feuerbach and Weilimdorf.

- **Infiltration in central city district**

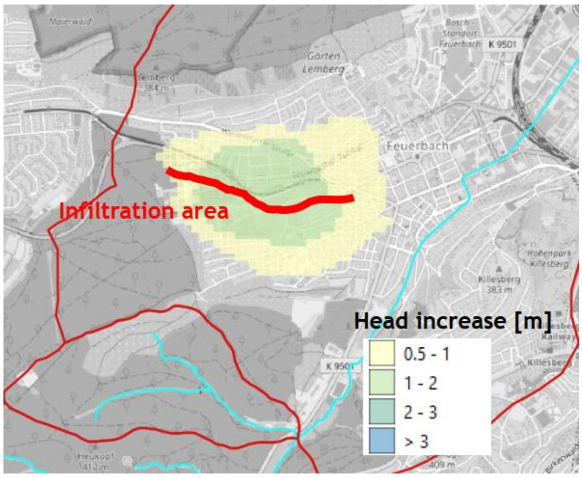
Figure 5 (upper image) shows the effects of infiltration into the aquifer Bochinger Horizont by a row of five wells along street B 295 with an overall input rate of 10 l/s. The chosen location corresponds with a comparatively high permeability zone within this aquifer. The lower images show effects on the underlying Grundgipsschichten und the uppermost quaternary aquifer.



Infiltration in aquifer Bochinger Horizont

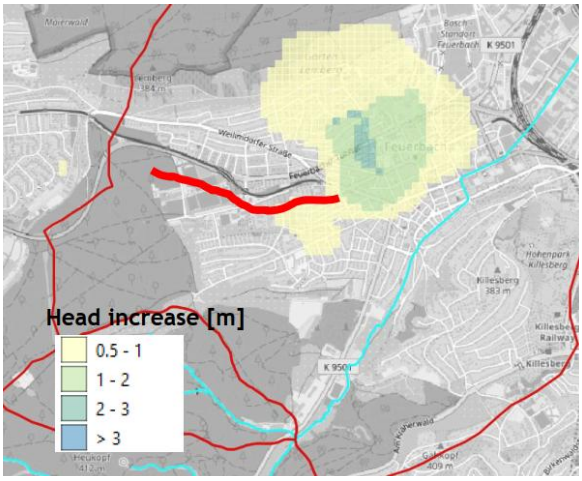
Geohydraulic Reactions in Bochinger Horizont

- Head increase of 0.5m up to a distance of 1 km, including Feuerbach city hall
- Head increase near infiltration area up to 3 m
- Groundwater levels are deeper than 4 m below ground surface.



Quaternary

- Head increase of 0.5 m up to a distance of 0.6 km
- Head increase near infiltration wells up to 1.5 m



Grundgipsschichten

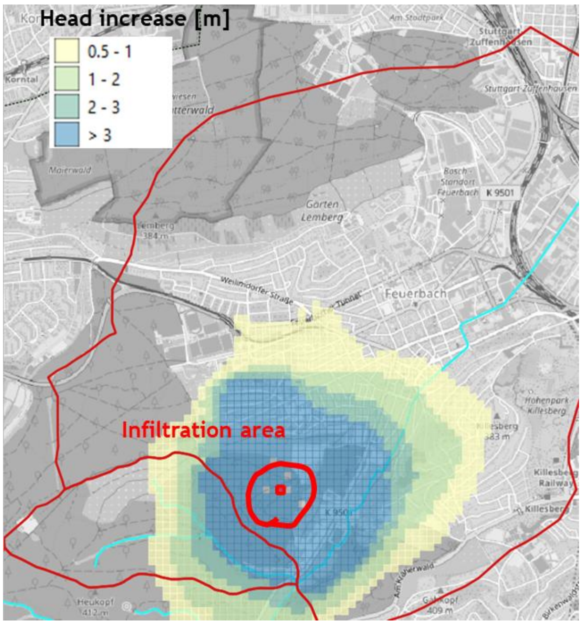
- Head increase of 0.5 m up to a distance of 0.6 km

Figure 5: Distribution of hydraulic levels following an infiltration of 10 l/s into Bochinger Horizont.

This option achieves distinct increases of water levels in the central city area, not only in the infiltration horizon Bochinger Horizont, but also in the shallow quaternary aquifer. However, water levels are still low enough to avoid the risk of flooding basements.

Infiltration in the western city part

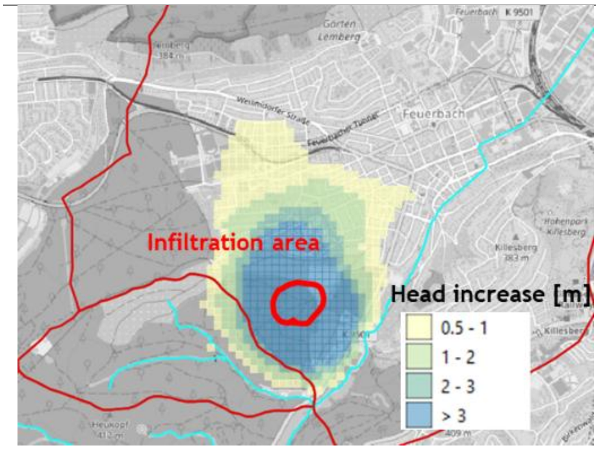
Figure 6 shows the effects of infiltration into the aquifers Mittlerer Gipshorizont and Bochinger Horizont with a rate of 10 l/s. The chosen location corresponds with a low permeability zone within this aquifer.



Infiltration in aquifers Mittlerer Gipshorizont and Bochinger Horizont

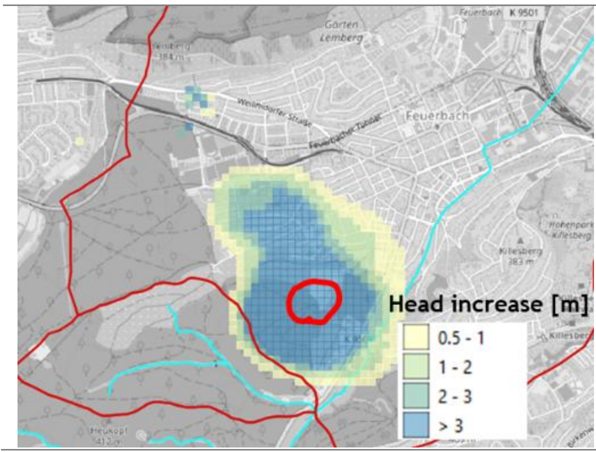
Geohydraulic Reactions in Bochinger Horizont

- 0.5 m head increase up to a distance of 1 km
- head increase near infiltration wells > 5 m
- minor effects on central city district
- high pressure due to low permeability



Quaternary

- Head increase of 0.5 m up to a distance of 1 km
- Head increase near infiltration wells up to 5 m



Grundgipsschichten

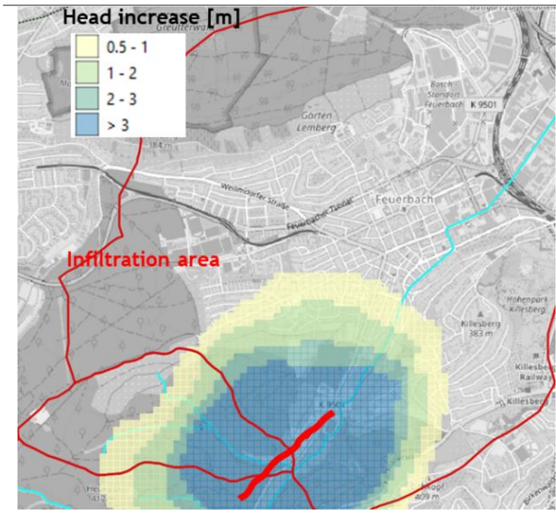
- Head increase of 0.5 m up to a distance of 0.6 km
- No effects on Feuerbach central district (city hall)

Figure 6: Hydraulic levels following an infiltration of 10 l/s into Mittlerer Gipshorizont and Bochinger Horizont

This option leads to high water level increases near the infiltration area, the risk of basement floodings cannot be excluded. The regional influence is limited and there are only minor effects on the central city district.

- **Infiltration in the southern city, near Feuerbach creek**

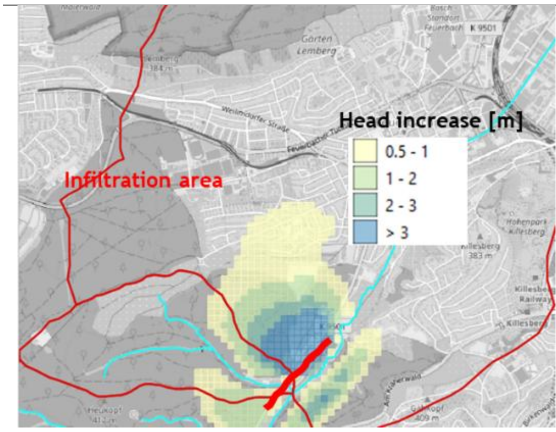
Figure 7 shows the effects of infiltration into the aquifers Mittlerer Gipshorizont and Bochinger Horizont with a rate of 10 l/s. The chosen location corresponds with a low permeability zone within this aquifer.



Infiltration in aquifers Mittlerer Gipshorizont and Bochinger Horizont

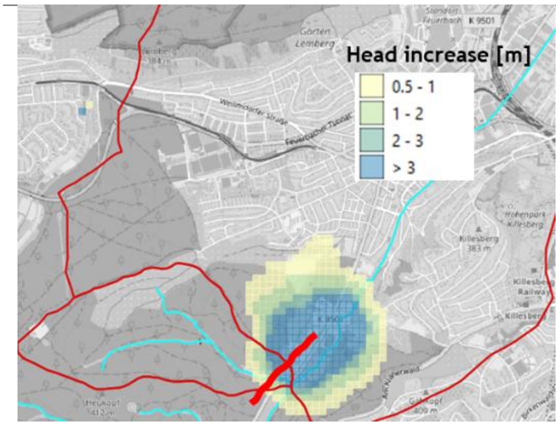
Geohydraulic Reactions in Dunkelrote Megel:

- 0.5 m head increase up to a distance of 1.7 km
- Head increase near infiltration wells > 5 m
- water table above terrain level!
- minor effects on central city district



Quaternary

- 0.5 m head increase up to a distance of 1 km
- 5m head increase near infiltration wells
- Water table nearly reaching ground surface



Grundgipsschichten

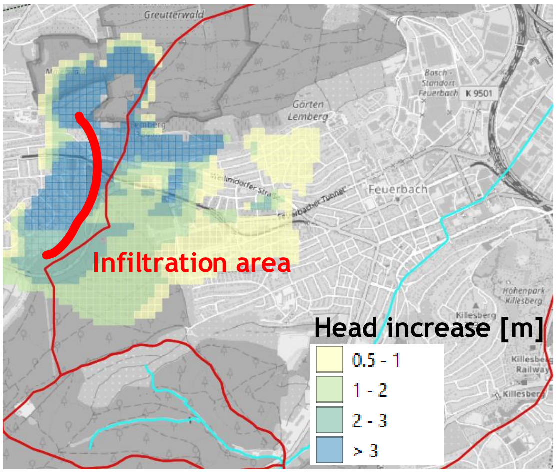
- 0.5 m head increase up to a distance of 0.6 km
- No effects on city district

Figure 7: Hydraulic levels following a 10 l/s infiltration into Mittlerer Gipshorizont and Bochinger Horizont

This option leads to high water level increases near the infiltration area, water table values above ground surface indicate a clear flooding risk. The regional influence is limited and there is hardly any influence on the central city district.

- **Infiltrations at western border of Feuerbach**

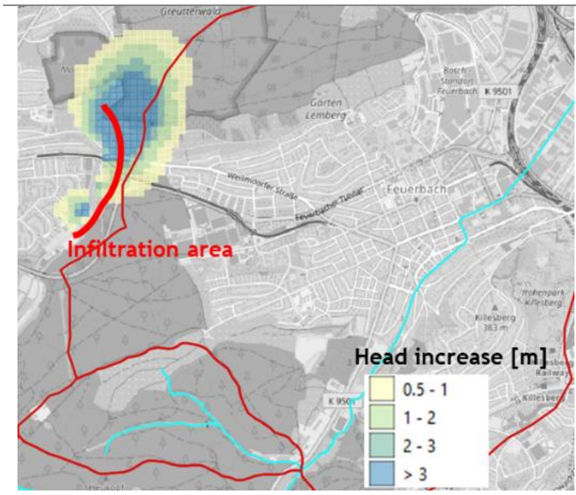
Figure 8 shows the effects of infiltration into the aquifers Quartär and Bochinger Horizont with a rate of 10 l/s. The chosen location corresponds with a high permeability zone in these aquifers.



Infiltration in aquifers Quartär and Bochinger Horizont

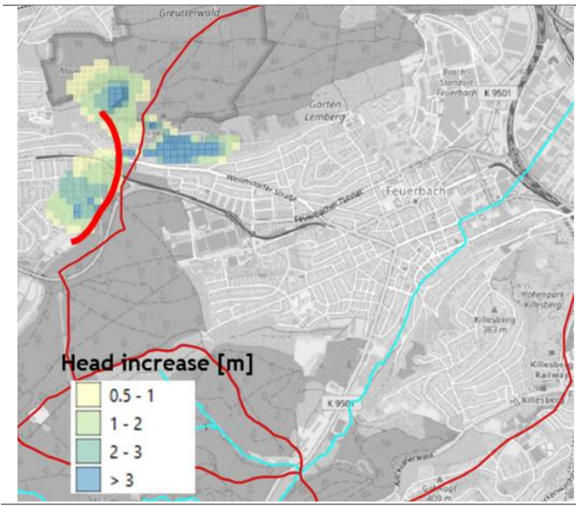
Geohydraulic Reactions in Bochinger Horizont

- 0.5 m head increase up to a distance of 1.6 km
- Head increase near infiltration wells 1.5 km
- Only minor effects on Feuerbach city center



Quaternary

- 0.5 m head increase up to a distance of 0.2 km
- Only local head increase



Grundgipsschichten

- Small influence area

Figure 8: Distribution of hydraulic levels following an infiltration of 10 l/s into Quaternary and Bochinger Horizont

This option achieves the highest regional elevation effects. However, due to the position of infiltration wells, the effects on the central city are limited. The risk of flooding basements can be excluded.

2.4. Using numerical models as prognosis tools

To understand the effects of an adaptation option within a local hydrogeological system, it is essential not only to characterise the area but also to represent the interactions among its components. In hydrogeology, numerical models are widely used for this purpose: they simulate groundwater processes mathematically and allow the testing of scenarios in complex systems, supporting informed groundwater-management decisions. In MAURICE, climate-change projections were integrated into the assessment framework for evaluating adaptation options. When working with climate data and groundwater models, it is important to consider:

- Climate data are usually available at global or large-regional scales, whereas groundwater processes are locally shaped by geology and soil conditions. Applying coarse-scale climate data to the fine resolution of a groundwater model introduces statistical uncertainties.
- Climate scenarios often exhibit a wide range of variability. While temperature trends show a stable increase, precipitation signals in models fluctuate significantly, which complicates the calculation of groundwater recharge.

In the groundwater model for Feuerbach, uncertainties also arise in short-term analyses and those limited to specific time periods. However, long-term modelling provides relatively reliable results regarding the development of groundwater head levels.

3. Analysis of adaptation options

Providing a robust analysis of adaptation options enables their comparison and selection by all stakeholders involved. To counteract the declining groundwater levels in Stuttgart-Feuerbach, several adaptation options are available. Following calculations by the MAURICE groundwater model, an additional water input of 12–20 l/s is required to compensate losses and initiate a trend reversal. Potential measures include reducing groundwater extractions and/or introducing additional water to the system.

- <u>Reducing water withdrawals</u> may be a feasible option in the construction projects that involve underground work. Another promising approach is the targeted design of groundwater remediation measures with the aim to avoid the widespread groundwater extraction and subsequent discharge into the sewage system. Both measures are realistic and feasible, however a reliable assessment of water quantities to be saved is currently not available.
- <u>Input of additional water to the system</u> can be achieved by:
  - Unsealing selected areas, though with a limited effect. Sealed surfaces should be removed and measures to allow precipitation to infiltrate should be taken to promote groundwater recharge.
  - Implementing measures to allow for local, near-surface infiltration of roof runoff and surface runoff. These measures must consider the local permeability conditions to prevent basement flooding.
  - Water input via infiltration wells. This was assessed through numerical modelling using an input rate of 10 L/s at different locations and aquifers. Infiltration effectiveness depends mainly on horizontal permeability, while vertical permeability controls how strongly overlying and underlying groundwater storeys are affected. Infiltration in low-permeability zones is not recommended, as it produces minor effects in the central district and may cause local head increases around the wells, with a risk of basement flooding. The most favourable results were obtained by placing wells in a high-permeability zone along the western border of Feuerbach. Impacts on critical infrastructure in the city centre are limited, while the inner-city district experiences a 1–3 m rise in groundwater levels without any associated flooding risk.

C. Guidelines for the implementation of agricultural managed aquifer recharge

1. Lessons learned from Milan's pilot action

Milan Pilot Action enabled the on-field experimentation of agricultural managed aquifer recharge (Ag-MAR) in a peri-urban setting close to Milan. The area presented many challenges: the coexistence of agricultural and urban areas, the presence of groundwater dependent ecosystems, the relationship between various stakeholders. Since the project included a simulation of future climate and irrigation derivations, a refined methodology had to be followed. This resulted in the need to overcome limits and learn from the implementation and iterations of tests. In this chapter, the main lessons learned from these activities are collected for future reference and for other projects encountering the same issues.

1.1. Area selection and preliminary analysis

- The **project area should be optimized to match the project goals**. In areas with hydrogeological diversity (e.g., springs), it is preferable to focus on smaller, more homogeneous areas to better evaluate the project's added value. In our Pilot Area, having a broader area meant the ability to consider impacts on a larger scale, but with less detail and resulting in more work needed to characterize and monitor the area. A **trade-off** between the accurate monitoring of a single area and the ability to reconstruct regional conditions needs to be considered when planning the project.
- **Historical data** are necessary to reconstruct past hydrogeological conditions, natural cycles and drivers. In our area, too few groundwater monitoring points were available, thus rendering the groundwater table reconstruction not reliable until monitoring activities started.
- The area was chosen mostly based on the presence of farmers who agreed to the experimentation to Consorzio Est Ticino Villoresi (project partner), thus limiting the factors identified before. Farmers were crucial for the Ag-MAR implementation in our case. Broadening the pool of farmers available via a survey can expand the choice of suitable areas for experimentation.
- Conducting an upstream climate risk and vulnerability assessment, in coordination with regional and European policy makers, is essential to orient research effectively. Following a clear structure from the beginning would have reduced inconsistencies.

1.2. Monitoring and data collection

- In dense and complex irrigation networks, **accurately identifying active elements** and their discharge points is more critical than general characterization. Rather than chasing precision, which is impossible at this scale, it can be more effective to embrace uncertainty and incorporate it into the results through specific uncertainty analyses.
- It is essential to **focus on high-value measurements**, such as monitoring inflow and outflow rates, while avoiding redundancies. For example, infiltration tests proved unnecessary when data on network losses were already available, ensuring that effort is not wasted on data that doesn't actively improve the final modelling.

1.3. Modelling process

- The **climate downscaling** techniques were refined by using techniques to reduce bias, such as analysing the range of temperature extremes rather than independent projections. This stemmed from cooperation among the developers and improved the quality of the baseline data.
- When considering the agricultural system, it is essential to use models capable of **integrating both physical phenomena and human decisions** to obtain realistic flow values in an irrigation system. Human behaviour modelling was achieved by weighting recent data. To simulate future human behaviour especially in contexts like agriculture, which is rapidly changing, it is more effective to use a "cyclo-stationary" approach based on the last 10 years rather than a thirty-year historical series, to better reflect current regulations and practices.
- It emerged a **need for a feedback loop** between "upstream" and "downstream" in the modelling pipeline. The project required the combination of three main models: one for future river and irrigation availability, one for the agro-hydrological system, and one for the groundwater system. However, an iterative process ensuring continuous communication among developers and cross-checking of their practices was missing. As a result, outputs generated downstream could not be used to refine or adjust the upstream scenarios. This iterative exchange was implemented between the agro-hydrological and groundwater models, but not across all three models.
- The **model development timeline** was **constrained** by the data gathering process, since the groundwater model calibration could be achieved at great precision only when September 2025 data were collected, after monitoring the groundwater levels for two summers and one winter with the Ag-MAR implementation. The model uses a weekly timestep and a fine spatial grid, requiring a long time series to achieve a reliable calibration. Delays in field activities during the first project year further affected the process: the first winter test could not be monitored with the high-frequency sensors used in the second winter and therefore could not be used to calibrate the model for representing Ag-MAR implementation.

1.4. Communication and transparency among partners and stakeholders

- **Early and inclusive stakeholder involvement** was a key in the project development. Dialogue between all levels (farmers, consortium, decision-makers) must occur from the beginning of the project to identify the real needs of the end user. An initial lack of transparency, especially between the consortium and farmers, can generate mistrust and hinder the collection of accurate data.
- Punctuality in objectives, clear meeting minutes ("who does what"), and regular meetings (including hybrid mode) are key elements for operational success. Across the project timeline, this was achieved successfully thanks to internal management and communication from the Pilot Action Leader.

1.5. Feedback from farmers participating in the project

At the end of the experimentation phase, we asked the three farmers who participated in the project to answer questions on the development of the project itself as well as results they could directly observed. Below their answers are summarized. The whole surveys are provided as an attachment to the deliverable.

- **Participation in the project**

Farmers' participation was driven by their interest in demonstrating the benefits of water circulation in agricultural areas during winter, effects they had observed in the past but never quantified. They perceived clear advantages in implementing the measure, with the only disadvantage being additional work during winter, deemed however minimal. Their tasks consisted mainly of opening the gates to the fields to be irrigated during winter and monitoring that the water did not overflow from canals. If a field got flooded, they then would switch the water flow to another one, alternating. Communication with Politecnico di Milano was deemed clear and transparent, and the ability to adjust the project activities to their needs (for example, due to environmental or unforeseen conditions) was appreciated. An interest to see collected monitoring data emerged, further highlighting their interest in the project results.

- **Observed impacts of the tested adaptation measure**

All farmers reported additional positive impacts from the adaptation measure beyond its primary objective of increasing aquifer storage. Water circulation in the canals during winter reduced conveyance losses during the following summer irrigation season, allowing higher water volumes to reach downstream fields. Continuous winter flow also prevented vegetation from growing in the canal beds and along the banks, reducing the need for pre-season maintenance. Farmers further observed that lowland springs maintained higher flows later into the year compared with winters without the measure, extending the period during which this water could be used. The final effect was identified in a change in the landscape and fauna, since water over the field attracted birds (snipes, ducks) during the winter season, bringing more life and scenery to the area.

- **Future availability and conditions**

When asked if they would be interested in implementing the measure also beyond the project lifetime, all three farmers responded positively. Two of them would do it even if they had to pay for the water, as they already did in the past. One of them would not since it wouldn't have the same direct economical return as summer water (used to grow crops). All of them would prefer a solution where the water is free or comes with incentives to implement the measure. It was noted how bringing more farmers into practicing the measure would lead to an increased effect, even if only keeping the water inside the canals and not distributing it to the fields. The implementation over contiguous areas would have a multiplying effect, bringing the observed impacts at broader scale.

2. Guidelines comprising technical and non-technical requirements for Ag-MAR implementation

Agricultural Managed Aquifer Recharge (Ag-MAR) refers to transferring excess surface water during periods of water availability onto agricultural land to enhance groundwater recharge (Levintal et al., 2023). As part of the broad range of MAR solutions, Ag-MAR can support water demand management, which is an increasingly urgent need as climate change intensifies drought frequency and exacerbates water scarcity. Embedding Ag-MAR within integrated water management strategies can accelerate its adoption, especially where MAR solutions are limited by lack of awareness, insufficient aquifer knowledge, risk perception barriers, and incomplete policy frameworks (Dillon et al. 2020).

This section provides practical guidance for planning and implementing Ag-MAR interventions drawing on the experience of Milan pilot action. It highlights technical and non-technical considerations that are broadly transferable across a range of contexts, helping identify opportunities for Ag-MAR testing or scaling, from local trials to regional applications.

In MAURICE, Ag-MAR was conceived as a drought adaptation measure. Therefore, the Climate-ADAPT framework for local and regional adaptation guided the implementation process. However, different frameworks for MAR and Ag-MAR implementation exist in literature, and insights from MAURICE can complement them. Hereby we propose a combined MAURICE framework for Ag-MAR implementation in table below and the stages are described in the following sections.

Stage	MAURICE framework for Ag-MAR implementation	Correspondence with literature framework for Ag-MAR implementation (Levintal et al., 2023)	Correspondence with Climate-ADAPT framework for climate adaptation measures
1	**Prepare the ground for Ag-MAR**	Preliminary investigations	Preparing the ground for adaptation
2	**Assess Ag-MAR suitability**		Assessing climate risks and vulnerabilities
3	**Assess Ag-MAR feasibility**	Advanced site investigations	Assessing adaptation options
4	**Implementing Ag-MAR**	Site preparations Flooding	Implementing the adaptation measure
5	**Monitoring**	Post-flooding	Monitoring, Evaluating and Learning

Figure 9: MAURICE framework for Ag-MAR implementation and correspondence with relevant literature frameworks.

2.1. Prepare the ground for Ag-MAR

- **Site selection and scale definition**

Effective, long-term Ag-MAR implementation depends on selecting suitable sites and defining an appropriate geographic scale. Experience from MAURICE shows that scale should be aligned with available resources, especially in areas with high hydrogeological heterogeneity or numerous water features that increase system complexity. It is preferable to focus on smaller, more homogeneous areas to better assess Ag-MAR effects on the system and reduces the effort and resources required for site and characterization and monitoring. At a regional scale, lower spatial resolution often limits the ability to capture local dynamics and increases uncertainty. For this reason, Ag-MAR feasibility should first be assessed at local scale, and results can then inform stepwise expansion to broader areas.

- **Data collection and analysis**

A systematic review of existing data is essential in the early stages. Key information for Ag-MAR includes hydrogeological maps, groundwater level records, land use data, irrigation practices, soil characteristics and climate data. As demonstrated in MAURICE, well-distributed historical datasets are crucial to reconstruct the aquifer conditions and understanding system drivers. Previous studies (e.g., development and application of a groundwater model comprising the area of interest) can provide valuable insights into the system behaviour. This initial analysis helps identify data gaps where targeted monitoring or short-term field investigations may be needed. In addition, national, regional and local planning instruments often contain relevant information on water management and climate trends, supporting the identification of consistent patterns and policy priorities that should be considered when planning Ag-MAR.

2.1.1. Non-technical aspects

- **Identification of resources**

Although Ag-MAR can be cost-effective when it builds on existing infrastructure, implementation still requires early financial planning. Securing financial resources is essential for equipment, monitoring tools, and later-stage investments. Identify mainstreaming opportunities for Ag-MAR into local and regional planning instruments helps recognize funding opportunities and ensure alignment with policy frameworks. Long-term sustainability depends on integrating Ag-MAR within regional funding schemes and sectoral plans.

Human resources at management, technical, and operational levels are equally important. One important constraint for Ag-MAR is the limited number of farmers willing or able to participate. Surveys can help determine the pool of interested farmers and guide the selection of suitable areas for experimentation.

Access to technological resources, such as monitoring equipment, modelling tools, and data-processing capabilities, is also critical to ensure high-quality scientific and technical outputs.

- **A solid governance structure to secure active stakeholder involvement**

Ag-MAR benefits from collaborative and clearly structured governance. Stakeholders should be actively involved from the earliest stages, and governance arrangements should consider both short- and long-term outcomes. Ag-MAR typically needs the collaboration irrigation consortia, water authorities, regional governments, farmers, and research institutions with well-defined roles and coordinated decision-making mechanisms that align Ag-MAR objectives with broader water management and climate adaptation strategies.

Based on MAURICE experience, effective implementation of Ag-MAR relies on the involvement of:

- **Regional governments,** which create the political and regulatory conditions for Ag-MAR and ensure coherence with regional water-management and climate-adaptation goals. They coordinate the overall management dimension of Ag-MAR.

- **Local water, irrigation, and agricultural management entities**, which coordinate data collection, inter-sectoral planning, and operational activities. They act as a bridge between management and technical implementation.

- **Universities and research institutions**, which support data analysis, characterization studies, literature and best-practice reviews, and the development of evidence-based frameworks. They define the technical foundations of Ag-MAR.

- **Local communities and farmers**, represented through relevant associations, who provide essential information on needs, constraints, and willingness to participate in experimentation and long-term implementation. They are central to the operational dimension of Ag-MAR.

In MAURICE, two coordinated working groups, a technical-operational group and a management group, were established to divide the tasks for Ag-MAR implementation. Regular meetings ensured progress tracking, continuous evaluation and exchange of perspectives.

Social acceptability

Social acceptability is closely linked to governance but is often overlooked in MAR implementation. Because Ag-MAR depends on cooperation with irrigation consortia and farmers, it should be assessed from the beginning. As shown by Chen et al. (2024), surveys are effective tools for evaluating social acceptance and informing the social dimension of feasibility assessments. Their findings indicate that while two-thirds of respondents supported MAR, concerns remained regarding environmental impacts and groundwater entitlements. Supporters tended to be business-oriented and favourable to innovation and collective groundwater management tailored to local conditions. This suggests that Ag-MAR uptake can be strengthened in regions where farmers and citizens actively promote MAR through bottom-up initiatives. Hence, transparent communication on Ag-MAR's environmental impacts, implications for water entitlements, and potential costs for water users is essential to build trust and support.

2.2. Assess Ag-MAR suitability

This preliminary assessment should aim to determine the objectives of the Ag-MAR intervention and whether the selected site is suitable. This can be evaluated through the steps described below.

2.2.1. Technical assessment

Characterisation of the area

Understanding the physical and hydrogeological context is essential for evaluating Ag-MAR suitability. Dillon et al. (2020) recommends beginning with aquifer-suitability mapping using GIS and multi-criteria decision analysis (MCDA). For Ag-MAR, the screening process should consider aquifer type, crop types, agricultural practices, and soil permeability. The presence of permeable soils, shallow water tables, and existing irrigation or drainage infrastructure that can facilitate recharge with minimal investment.

Suitable areas should then be characterised in terms of surface-groundwater interactions, including drainage features and groundwater-dependent ecosystems. Aquifer dynamics, particularly interactions with wells and irrigation systems, must be assessed to understand how recharge water will move through the system.

As highlighted by Levintal et al. (2023), subsurface heterogeneity strongly influences infiltration pathways and storage capacity. Characterising this heterogeneity is critical for successful recharge and can later be refined through model simulations to estimate the duration and magnitude of groundwater-level responses under different Ag-MAR regimes.

Efforts to improve site characterisation should build on existing knowledge and prioritise high-value measurements that directly support the development of a conceptual model of the system. This phase should precede numerical modelling, focusing on data that can be integrated into the modelling workflow and fill key gaps in understanding system behaviour.

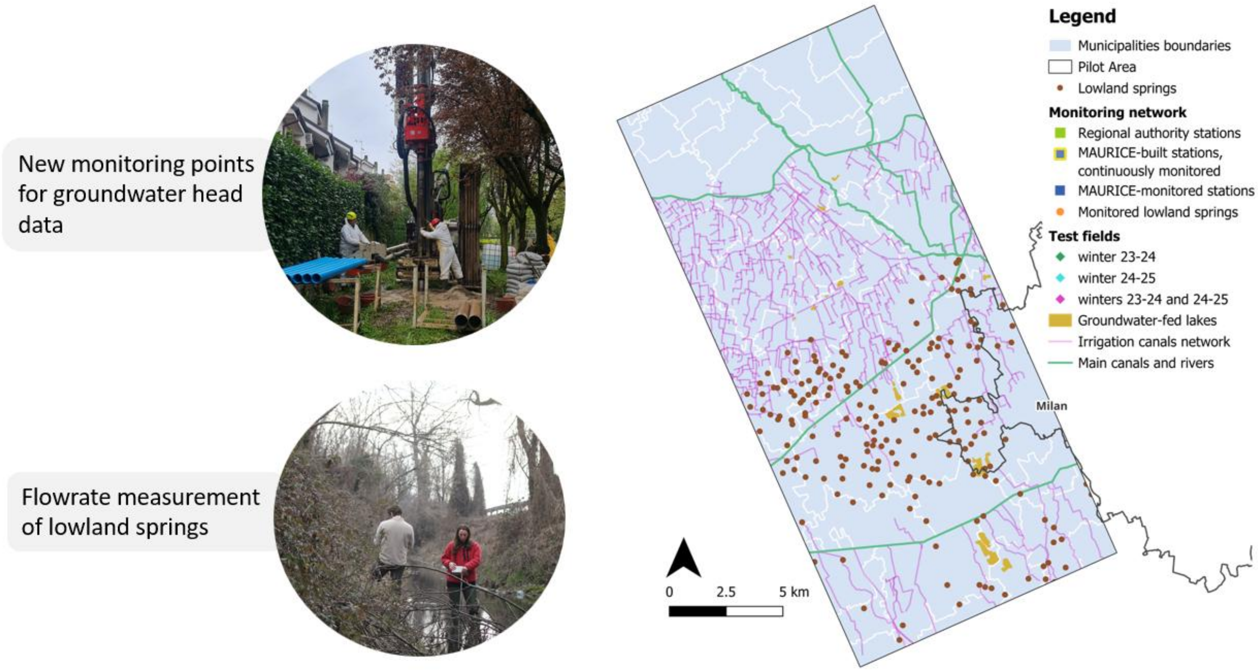


Figure 10: Field data collection to enhance the characterisation of Milan pilot area.

- **Vulnerability to climate risks**

MAR is particularly valuable in regions vulnerable to drought risks that rely heavily on groundwater. It can help increase dry season flows and provide ecological benefits, especially in regions with a Mediterranean climate where water demand peaks when surface water availability is low (Alam et al., 2021). Ag-MAR should be prioritised in areas facing recurrent or projected droughts, declining groundwater levels, or high irrigation demand. Vulnerability assessments should consider both current conditions and future climate scenarios, including changes in precipitation, temperature, and irrigation water availability. A robust climate risk assessment ensures coherence between identified risks and the rationale for Ag-MAR implementation.

In MAURICE, Ag-MAR was selected as an adaptation measure following the severe 2022–2023 drought in Milan. Climate projections for the pilot area indicated that droughts of similar magnitude are unlikely to become frequent locally. However, due to the regional climate heterogeneity across Lombardy, other areas remain more exposed and vulnerable to droughts. This means that Ag-MAR can still be considered a relevant drought adaptation measure available for Lombardy, but its primary role in the Metropolitan Area of Milan is to support integrated and climate resilient water management. This emphasizes the importance of conducting climate risk assessments in a timely manner and at appropriate spatial scales.

2.2.2. Compare against other options

Depending on the context, Ag-MAR might not be the only suitable option to achieve a climate adaptation or water management goal. Climate adaptation frameworks typically require a dedicated comparison of all available options. As shown by Harvey et al. (2024), this can be done by exploring alternative scenarios with stakeholders and local communities, for example, comparing the multi-year water storage benefits of MAR versus competing options such as surface water storage (e.g., large dams) or conjunctive use systems that integrate groundwater and surface water delivery. Such comparisons support collective decision-making on the most efficient water supply strategy for a given community.

In MAURICE, a set of selection criteria was co-developed with the stakeholders to assess aquifer-based drought adaptation options in Lombardy, which are shown in the table below.

Table 1 - Selection criteria to assess aquifer-based drought adaptation options in Lombardy.

	Type	Selection criteria
	Efficiency	• Stored and available water • Reduced drought risk for crop production
	Economic sustainability	• Implementation, operation and maintenance costs
	Environmental impact	• Groundwater level response • Lowland springs benefiting from increased flow
	Social impact	• Stakeholders involved • Farmers involved
	Regulatory feasibility	• Consistency with the regional adaptation strategy and sectorial plans • Compliance with regional water and agriculture regulations

2.2.3. Establish a clear Ag-MAR objective

According to Dillon et al. (2020), the primary target and advantage of MAR is the water security improvement. This aligns with integrated water management, climate resilience and sponge city approaches. As previously mentioned, in MAURICE, Ag-MAR was initially conceived as a climate adaptation solution in response to drought risk. However, it can be integrated in a broader water management logic to increase the probability of its long-term uptake and potential for upscaling.

MAR innovations rely on recharging aquifers during periods of surplus and extracting water when needed, offering a flexible and efficient storage solution. Hence MAR (and Ag-MAR) interventions can have multiple objectives. For example, MAR in Australian agricultural regions has been proposed as an innovative method to manage variable water availability, addressing water shortages, mitigating groundwater overuse, and reducing evaporative losses from surface storages (Harvey et al., 2024).

2.3. Assess the feasibility of Ag-MAR

Limited uptake of MAR solutions is often linked to uncertainties about their impacts (Harvey et al., 2024). A comprehensive feasibility study should therefore identify and address the main sources of uncertainty. Ag-MAR feasibility considerations can be grouped into technical and non-technical elements.

2.3.1. Key technical elements enabling Ag-MAR

Building on Levintal et al. (2023) and the MAURICE experience, the following key factors directly influence the design and operation of Ag-MAR systems:

- **Source water availability and quality**

  Ag-MAR requires a reliable source of water during periods of low competing demand, typically in autumn and winter. Surface water from rivers, lakes, or irrigation canals is commonly used. Availability depends on climatic conditions and regulatory constraints such as minimum in-stream flow requirements or surface-water rights (Levintal et al., 2023). Feasibility assessments should therefore evaluate not only current water volumes but also their future sustainability under different climate scenarios and projected socio-economic behaviours, including dam-operation rules that may affect winter flows.

Because Ag-MAR relies on existing conveyance infrastructure, the maximum flow rate that irrigation networks can safely handle is another critical factor.

Source water quality must also meet minimum standards. High nutrient loads or contaminants can percolate to groundwater, posing risks to water quality. Common contaminants of concern include nitrates, salts, pesticides, and metals, although these are often present at higher concentrations in soils than in the applied water (Levintal et al., 2023).

- **Soil and unsaturated zone**

  O'Geen et al. (2015) developed the Soil Agricultural Groundwater Banking Index (SAGBI) to assess soil suitability for recharge based on deep percolation, root-zone residence time, topography, chemical limitations, and surface condition. Proper soil characterisation is essential because prolonged flooding can alter hydraulic properties (Levintal et al., 2023), increasing the risk of clogging, one of the most common operational challenges in MAR (Dillon et al., 2020). Waterlogging is another risk, caused by excessive recharge that raises the water table into the root zone. As noted by Alam et al. (2021), waterlogging reduces aeration and soil temperature, increases salinisation, slows microbial activity, lowers yields, and increases plant vulnerability to disease. Site selection should therefore consider both clogging and waterlogging potential, favouring flood-tolerant crop types where necessary.

- **Cropping system suitability**

  Because Ag-MAR can reduce oxygen levels within the soil, in may inhibit root respiration, root growth and seed germination, ultimately causing a negative effect on crop yield (Levintal et al., 2023). A comprehensive Ag-MAR feasibility study should therefore account for crop tolerance to prolonged flooding conditions. Crops that are normally subject to flooded conditions may allow for easier integration of Ag-MAR into existing agricultural practices (Levintal et al., 2023).

2.3.2. Detect and address potential Ag-MAR related impacts

As noted earlier, social acceptability of Ag-MAR increases when potential impacts are clearly characterised and transparently communicated. The main environmental impacts to consider include the following:

- **Impacts on aquifer**

  Ag-MAR can affect groundwater quality depending on contaminant sources and biogeochemical processes in the vadose zone (Levintal et al., 2023). Agricultural soils often contain elevated levels of fertilizers, and nitrogen-cycle processes can lead to nitrate leaching, one of the primary concerns for groundwater quality. In MAURICE, this risk was mitigated by scheduling Ag-MAR flooding before the fertilisation period, reducing the likelihood of nitrate mobilisation and denitrification.

- **Impacts on climate**

  Although rather unexplored, Ag-MAR may influence climate-related feedback mechanisms, particularly through potential nitrous oxide (N_2O) emissions generated under prolonged anaerobic conditions during flooding (Levintal et al., 2023). If Ag-MAR is planned as a routine practice and long-term saturation of the vadose zone is expected, these emissions should be further investigated. At present, most MAR projects do not include monitoring of such feedback mechanisms, highlighting a gap for future research.

- **Impacts on ecosystems**

  Ag-MAR can provide ecological benefits, especially for groundwater-dependent ecosystems, depending on the location of recharge fields relative to groundwater flow paths feeding features such as lowland springs. Understanding these dynamics requires tools such as numerical modelling or time-series analysis of spring levels, aquifer levels, and precipitation. These analyses help determine whether Ag-MAR will enhance or potentially disrupt sensitive ecosystems.

2.3.3. Feasibility assessment through modelling

Models are helpful tools for assessing MAR systems because, when applied correctly, they help assess system constraints and minimize risks, thus justifying investments in planning and infrastructure (Ringleb et al., 2016). MAR-related models are typically grouped in five categories based on their objectives: groundwater flow, unsaturated flow, solute transport, reactive transport and watershed or water balance models (Ringleb et al., 2016). These models are commonly used to support MAR planning and optimisation, quantify geochemical processes during injection, assess recovery efficiency, and evaluate the interaction between injected and ambient groundwater (Ringleb et al., 2016).

In MAURICE, the pilot area was represented using two coupled numerical models:

- An agro-hydrological model, which performed a unit-based water balance integrating crop-water requirements and irrigation practices, producing percolation estimates.
- A groundwater-flow model, which simulated 3D transient flow in porous media. Percolation outputs from the agro-hydrological model were used as recharge inputs. The model incorporated well data, groundwater-level measurements, and hydrostratigraphic information, and was calibrated for hydraulic conductivity (aquifer and lowland springs) and specific yield.

The coupled modelling system was then used to simulate Ag-MAR performance under future water shortage scenarios and with optimized positioning of irrigated fields (Figure 11).

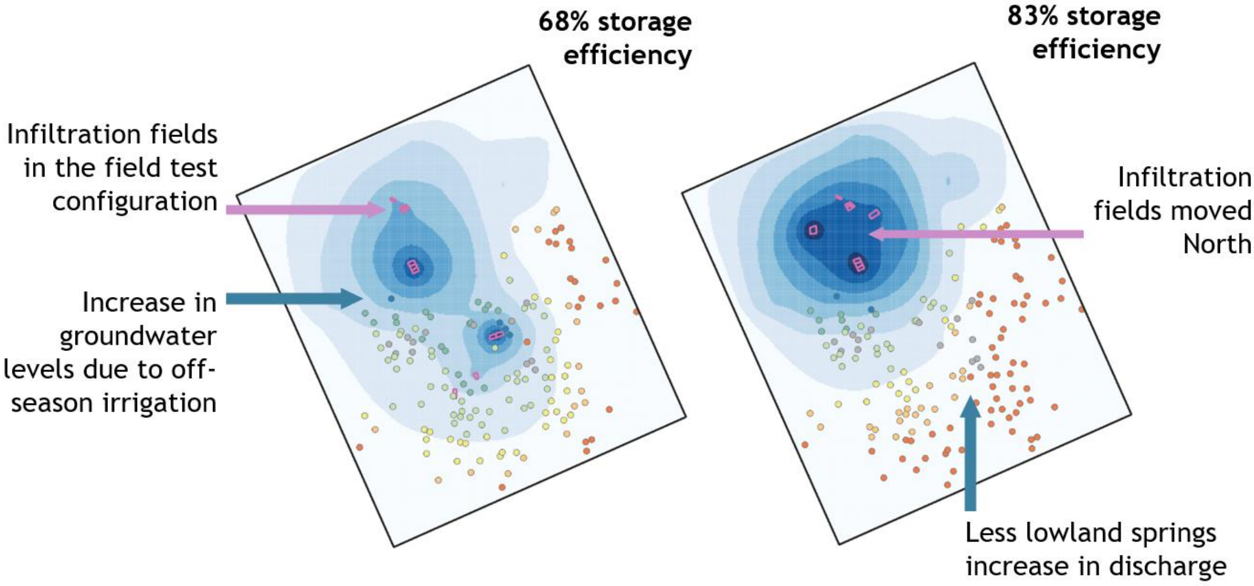


Figure 11. Model results showing changes in Ag-MAR efficiency depending on the position of irrigated fields with respect of the lowland springs present in the pilot area.

Climate variables were derived by statistically downscaling three regional climate model outputs under the IPCC RCP 8.5 scenario. Two machine learning models (LSTM) were applied to estimate future water availability in the main irrigation canal, the source of water for the Ag-MAR intervention (Figure 12).

Projected flow in Villoresi irrigation canal [m3 s-1]

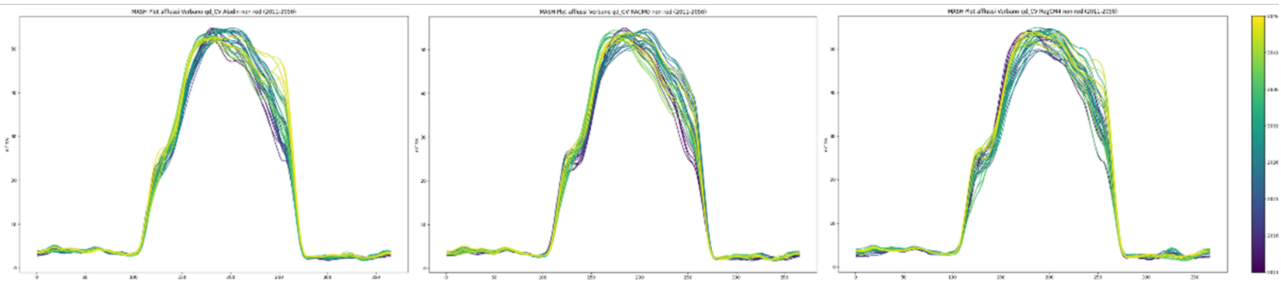


Figure 12. Projected flow in Villoresi irrigation canal according to three regional climate models (ALADIN, RACMO, RegCM4).

High-quality data are essential for accurate hydrogeological parameterisation and robust model calibration. Feasibility studies should also explicitly account for uncertainties in measurements and model predictions, as these uncertainties play a critical role in guiding decision-making and evaluating the reliability of Ag-MAR implementation.

2.3.4. Key non-technical elements enabling Ag-MAR

- **Regulatory and Legal aspects**

Water laws and regulations are often a major barrier to Ag-MAR because they typically focus on the volume and timing of water diversions rather than recharge activities (Levintal et al., 2023). A feasibility study should therefore assess all relevant regulatory components, including permitting procedures, water-concession frameworks, and environmental and agricultural regulations. Based on the MAURICE experience, early engagement with competent authorities is essential to identify regulatory constraints and opportunities. This engagement should be embedded within the broader governance structure, ensuring continuous communication between institutions and stakeholders throughout the implementation process.

- **Economical aspects**

Costs represent another significant barrier for Ag-MAR implementation. These include direct (project planning, infrastructure) and indirect components (monitoring systems, economic incentives) (Levintal et al., 2023). Beyond estimating operation and maintenance costs directly related to the physical components of Ag-MAR, a feasibility study should include a cost-benefit analysis for farmers and irrigation consortia to identify appropriate incentive mechanisms. Such mechanisms should compensate for perceived risks to crop health and for any additional costs related to water use (Levintal et al., 2023). Ag-MAR also generates broader economic benefits related to sustainable groundwater management, environmental protection, and long-term resilience. These benefits often outweigh the costs of environmental degradation and future remediation, making Ag-MAR a valuable multi-generational investment (Levintal et al., 2023). More detailed assessments can draw on hydro-economic approaches such as the one proposed by Gailey et al. (2019), that integrates hydrologic modelling with economic constraints reflecting real decision-making by groundwater managers.

- **Governance aspects**

As discussed earlier, Ag-MAR requires a collaborative governance structure. Implementation should be supported by dedicated technical and management groups: Technical functions include monitoring, modelling, data analysis, and site optimisation, while management functions include stakeholder engagement, coordination, communication, and the definition of operational rules. Clear agreements are needed on responsibilities, data-sharing protocols, and groundwater-use rules during and after recharge. Continuous engagement with stakeholders and local communities is essential. Communication channels should be established to ensure transparent data sharing at the management level and accessible information for farmers. Direct dialogue with farmers and local communities helps determine whether the proposed Ag-MAR intervention is technically feasible and compatible with existing agricultural practices.

2.4. Implementing Ag-MAR

2.4.1. Recharge techniques and infrastructure

Ag-MAR is one of the most widely applied MAR schemes because agricultural fields near rivers often require minimal water transport and are located at low elevations, reducing pumping needs (Chen et al., 2024). Implementation should therefore prioritise low-impact, cost-effective techniques that make use of existing infrastructure. New infrastructure should be considered only when existing systems cannot meet recharge or abstraction objectives. In MAURICE, two approaches were tested: Winter irrigation of agricultural fields, and circulation of water through permeable canal networks. Based on MAURICE's experience, it is essential to account for farmers' operational capacity to carry out Ag-MAR activities. Although Ag-MAR resembles standard irrigation practices, flexibility is important. In MAURICE, irrigation canals were kept open throughout winter, allowing farmers to irrigate when convenient and adapt to their field conditions. At the network level, a key infrastructure constraint is the maximum flow capacity that irrigation consortia can manage without causing operational issues.

2.4.2. Design and operational aspects

Ag-MAR design and operation should be adaptive and guided by monitoring. Insights from site characterisation and model simulations should inform the optimal positioning of recharge fields and the operational strategy. Ideal Ag-MAR operation aims to recharge as much water as possible when crops are not in active growth. However, excessive ponding can cause oxygen depletion and root damage (Chen et al., 2024). As suggested by Chen et al. (2023), intermittent flooding is recommended to allow soil drying and oxygen recovery, so the operational objective is to maximise recharge while maintaining healthy root-zone oxygen levels.

Therefore, key operational considerations include:

- Activation thresholds based on groundwater levels and risks of waterlogging or soil clogging.
- Crop compatibility, ensuring recharge does not interfere with sensitive growth stages.
- Coordination with agricultural calendars, particularly avoiding Ag-MAR after fertilisation to reduce nitrate-mobilisation risks.
- Alignment with canal-maintenance schedules to ensure uninterrupted water delivery.
- Clear procedures for extracting and using stored groundwater during droughts. In MAURICE, due to water use and irrigation policy, it has been proposed to abstract the stored water through emergency well fields managed by the irrigation consortium.

In MAURICE, Ag-MAR was tested during winter. If Ag-MAR is conceived as a drought-adaptation measure, it is necessary to decide whether it will be implemented preventively (before drought onset) or correctively (after drought impacts are observed).

2.5. Monitoring

Monitoring data should feed into a Monitoring, Evaluation and Learning framework to continuously improve Ag-MAR practices. As highlighted by Dillon et al. (2020), sustained monitoring and transparent sharing of results are essential for improving process understanding and ensuring reliable MAR systems capable of supporting resilient water supplies.

Both the aquifer system and Ag-MAR should be monitored continuously. Key elements include groundwater level observations, early detection of groundwater quality or crop quality degradation, and identification of clogging or water logging in agricultural fields. These parameters can be integrated into an Ag-MAR control scheme, such as the one as proposed by Chen et al. (2024), which evaluates Ag-MAR performance based on two factors: oxygen deficit ratio for crops and recharging water volume. Levintal et al. (2023) suggest monitoring different parameters during and after flooding:

- During flooding: surface-water quality and quantity, root-zone conditions, and recharge rates.
- After flooding: crop yield and any signs of soil or groundwater degradation.

A robust monitoring framework is therefore essential, with data centrally processed and shared to support decision-making. In MAURICE, the after-project monitoring proposal includes both a methodological approach and a set of indicators.

Monitoring and evaluation approach

Post-project monitoring is structured around three main activities:

- Data gathering, processing, and sharing, carried out in collaboration with environmental and irrigation managers and supported by the MAURICE dashboard.
- Activation of new monitoring points to strengthen the monitoring network, improving both Ag-MAR operations and integrated water-resources management.
- Periodic meetings to review updates, assess Ag-MAR effectiveness, and adjust operational strategies.

A dedicated monitoring centre should be established to oversee piezometric levels and determine when Ag-MAR should be activated if groundwater reaches critical depletion thresholds. To enable the operation of such centre, it is key to stablish a permanent collaboration space with clear responsibilities, allocate sufficient resources, and prioritise monitoring parameters and indicators accordingly.

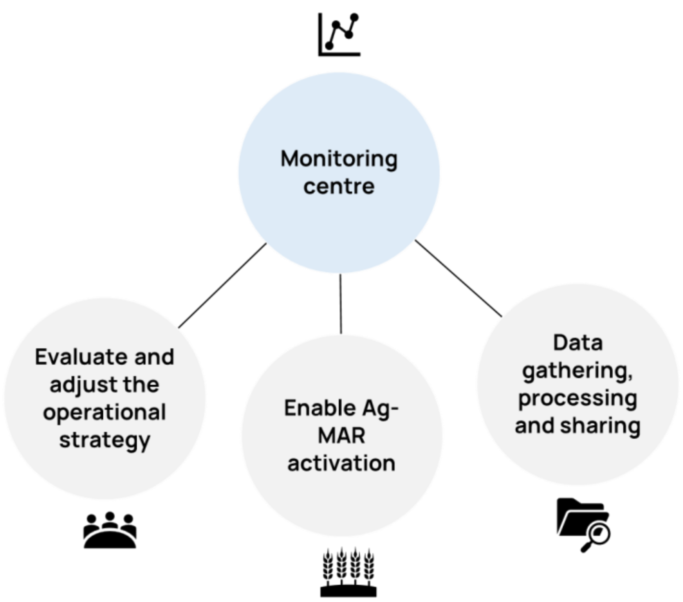


Figure 13. Summary scheme of MAURICE's monitoring and evaluation approach for Ag-MAR implementation.

■ Monitoring indicators

A set of monitoring parameters and indicators to assess the effectiveness of Ag-MAR as an adaptation measure was developed through multiple meetings with the stakeholders. These indicators were validated as relevant and appropriate for long-term evaluation.

Table 2 - Proposed set of monitoring parameters and effectiveness indicators for the implementation of Ag-MAR

Monitoring parameters	• Groundwater level
	• Hectares of irrigated agricultural land in the period November–February
	• Kilometres of irrigation canals that carry water year-round
	• Volume of infiltrated water
	• Volume of water distributed to the fields
	• Groundwater and Ticino River quality*
Ag-MAR effectiveness indicators	• % of water actually stored and available for consumption
	• % of demand met
	• % of summer irrigation demand met
	• Number of stakeholders and farmers involved
	• Number of lowland springs benefiting from increased flow

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