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Alpine Space
MARGIN

Deliverable 1.2.1

Catalogue of current strategies and measures

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MARGIN

MARGIN enables 5 cities in the Alpine Space to manage groundwater sustainability tackling effects of climate change and urbanization to foster city's climate-resilience. User-oriented, transnational tools and procedures will be established including risk analysis to monitor impacts on groundwater quantity, ecosystem and infrastructure, strategies and measures to cope with it and concepts to implement groundwater sustainability management into policy instruments at different administrative levels.

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1. Introduction

1.1 Objectives

Deliverable D.1.2.1 provides a comprehensive inventory and analysis of existing Strategies and Measures for groundwater sustainability management in urban environments. The catalogue is developed based on detailed city factsheets (Output O.1.1) from the four MARGIN pilot cities (Munich, Milan, Ljubljana, and Linz) and supplemented with review results that identify critical gaps and specific requirements for effective groundwater sustainability management in urban contexts.
This work is meant to provide a foundation for developing adaptation strategies in subsequent project phases and supports the creation of transnational best practices for groundwater sustainability management in Alpine cities.

1.2 Methodology

Strategies are defined as overarching plans or frameworks designed to address specific groundwater management problems, typically involving long-term goals and coordinated actions across multiple stakeholders and timeframes. **Measures** are specific, concrete actions or interventions implemented to achieve the objectives outlined within these broader strategies. It is important to note that many measures rely on and build upon existing monitoring networks and data management systems, creating interconnections with the monitoring practices detailed in Deliverable D.1.1.1 and the regulatory frameworks examined in Deliverable D.1.3.1.

Data collection employed a multi-source approach including local literature review, stakeholder interviews, collaborative workshops, online resources analysis, and comprehensive policy review. The methodology engaged municipal departments, environmental agencies, utility companies, urban planning authorities, and technical experts across all pilot cities (for further information on the involved parties see D.1.1.1). Four key dimensions of groundwater sustainability management are addressed: groundwater quantity, groundwater thermal use, groundwater quality, and groundwater ecosystem management. The analysis categorizes approaches into measures - Technical and Analytical tools (e.g., monitoring systems, numerical modelling, environmental impact assessments, technical standards, and analytical methods) - and Strategic and Policy frameworks (e.g., municipal strategies, regional policies). Existing Monitoring & Data Management practices, along with Regulatory and Governmental Measures and Frameworks, are referenced succinctly where necessary to provide context for in-place measures and strategies. They are detailed and evaluated more comprehensively in D.1.1.1 and D.1.3.1, respectively.

Effectiveness assessment evaluates coverage (spatial, temporal, and thematic scope), compliance (regulatory adherence and technical standards), impact (quantitative outcomes), stakeholder acceptance (institutional support and public acceptance), and sustainability (long-term viability and adaptive capacity). This is complemented by a systematic inter-city comparison, incorporating stakeholder requirement rankings and expert reviews.

1.3 Scope and Limitations

The catalogue covers the four MARGIN pilot cities and relevant surrounding areas (also called pilot areas), including strategies at municipal, regional/federal state, national, and European levels. The temporal scope encompasses strategies implemented within the past 10-20 years, with focus on currently active measures and forward-looking strategic documents. The analysis includes groundwater quantity, thermal use, quality, and ecosystem management strategies in the city's context. Surface water management, general water supply systems, wastewater treatment, and agricultural practices are excluded unless directly linked to urban groundwater management.

Methodological limitations include variation in data availability and formats across cities, language constraints, and focus on documented rather than informal practices. Analytical constraints include limited quantitative performance data, challenges in attributing outcomes to specific interventions, and differences in hydrogeological conditions and governance structures that limit direct comparability between cities.

2. Catalogue of Existing Strategies and Measures

Linz

Groundwater Quantity

The eHYD groundwater monitoring network is part of Austria's nationwide hydrographic system and covers also Linz, providing also real-time data on groundwater levels for chosen wells. In Linz it is supported by a network of approximately 250 measurement stations, some of which are equipped with data loggers. These stations enable the creation of groundwater contour maps and provide data for monitoring groundwater levels. Although not being part of a specific climate change and/or urbanization adaptation strategy this monitoring network (described in more detail in D.1.1.1) provides a foundation upon which additional strategies and measures to address climate change-related challenges have been developed and can be built upon.

Existing Strategies and Measures

Technical and Analytical Tools:

- Numerical Modelling for Groundwater Impact Assessment of Large Structures is an important tool in Linz. Large facilities are required to maintain models to ensure groundwater sustainability. A national guideline on numerical modelling for groundwater is available (ÖWAV-Regelblatt 222; more information in D.1.3.1).

- The study Groundwater Management Linz (2004), documented Linz's hydrogeological and thermal groundwater conditions and serves as a backbone for future groundwater research. Technical tools for future groundwater management planning included:
    - groundwater balance calculations,
    - temperature monitoring networks,
    - plausibility analysis of measurements,
    - thematic mapping with isoline/point/bar/area displays, and
    - hydrogeological cross-sections

Strategic and Policy Frameworks:

- Upper Austria's Drinking Water Future (2005): The strategy of the federal state of upper Austria prioritizes the sustainable use of groundwater resources by promoting regional and local water extraction systems tailored to settlement sizes. The strategy outlines comprehensive measures across five core areas: Groundwater Protection through agricultural partnerships and spatial planning safeguards; Distribution Structure preservation favouring local water sources over regional networks; Organizational Structure maintaining public/cooperative ownership while rejecting privatization; Individual Water Supply promoting central systems in settlements with quality standards for house wells; and Crisis Preparedness requiring risk analyses and backup systems.

- Drinking water Security Plan (2023): the strategy's primary goals include ensuring the long-term availability of high-quality and sufficient drinking water in Austria, adapting to challenges posed by climate change, and promoting sustainable water management practices. The drinking water security Plan was issued by the BML (Bundesministerium für Land- und Forstwirtschaft, Regionen und Wasserwirtschaft). The responsible government authorities from the federal states and the national institution BML will improve the data foundation. This will enable forward-looking planning and preparation of measures in the event of water scarcity. Specific measures of the Drinking Water Security Plan (2023) focus on infrastructure resilience through supraregional networks and backup sources, resource protection via groundwater exploration and expanded protection zones, emergency preparedness with a four-stage crisis response system, and enhanced monitoring through quarterly data exchanges and improved forecasting. The strategy measures prioritize also systematic pipeline renewal, strategic land acquisition for future resources, and research investment. Public awareness campaigns and strengthened legal frameworks support conservation efforts. Further measures ensure priority allocation for drinking water during shortages while maintaining federal-state coordination for comprehensive water security management.

- 1st Linz Climate Strategy (2019): The strategy, issued by the Municipal department for Planning, Engineering and Environment (Planung, Technik und Umwelt – PTU), aims to enhance the city's resilience to climate change by implementing measures that address urban heat, biodiversity, and sustainable development, fostering a liveable and climate-adapted urban environment. The broader climate adaptation efforts include measures related to water management, such as addressing urban heat islands, improving water retention through the "sponge city" concept, and protecting natural ecosystems, which indirectly contribute to sustainable groundwater quantity management.

- Climate Adaption Concept Future Linz (2023): The strategy, issued by the Municipal department PTU, focuses on enhancing the city's resilience to climate change by addressing risks such as water scarcity, local flooding, and increased irrigation needs. This concept builds open the 1st Linz Climate Strategy (2019) and defines the climate change adaptation. Broader climate adaptation efforts include measures like rainwater harvesting systems, retention areas, and improved water transport infrastructure. These initiatives aim to mitigate water-related challenges and indirectly support sustainable groundwater quantity management by promoting efficient water use and reducing stress on natural water systems.

Effectiveness and Identified Gaps in Groundwater Quantity

Technical and Analytical Tools

- **Effectiveness**:
  - Analytical tools provide valuable insights for assessing the impact of urban development and infrastructure on groundwater.
  - Numerical modelling is highly effective for evaluating sustainable groundwater management in Linz. The large eHYD monitoring network provides valuable insights and technical baseline documents like Groundwater Management Linz (2004) are important for decision making and further studies.
- **Gaps and Requirements**:
  - Limited integration of analytical results into advanced systems, such as GIS, reduces the potential for improved visualization and decision-making.
  - The city of Linz has expressed the need for high-resolution groundwater level maps and trend analyses to better understand and manage groundwater resources.

- There is a need for more advanced tools to support long-term trend analysis and predictive modelling for proactive groundwater management.
- Important comprehensive baseline studies like Groundwater Management Linz (2004) could support the management of groundwater sustainability if regularly updated.

Strategic and Policy Frameworks

- **Effectiveness**:
  - Existing frameworks prioritize sustainable groundwater use and address long-term challenges, such as climate change and urban development.
- **Gaps and Requirements**:
  - Mechanisms for engaging stakeholders, including local communities, the agricultural sector and industries, need to be strengthened to enhance the implementation and acceptance of strategic measures.

Groundwater Thermal Use

Existing Strategies and Measures

Technical and Analytical Tools

- Environmental Impact Assessment Procedures: The environmental impact of geothermal installations is assessed following federal guidelines (ÖWAV-Regelblatt 207, more information in D.1.3.1), which provides comprehensive technical guidance for thermal groundwater and subsurface systems. Key tools include the SIA 384/6 calculation method for geothermal probe sizing and the Ingerle-Rauch analytical method for thermal plume prediction. The document offers also Excel-based calculation tables for thermal computations and recommends Thermal Response Tests (TRT) for subsurface property assessment. Numerical modelling software like FEFLOW supports complex analysis scenarios.

Strategic and Policy Frameworks

- Local Technical Standards and Guidelines:_The city adheres to standardized requirements for geothermal installations, including a maximum allowable temperature spread of 6 K. Installations designed solely for cooling purposes are no longer approved, reflecting a shift toward more sustainable and balanced thermal groundwater use.

- Linz aims to achieve climate neutrality by 2040. As part of this effort, the city has adopted the comprehensive Climate Neutrality Industrial City Concept 2040 (2024), which aligns with the strategic mission of the Federal Ministry for Climate Protection (BMK) to support climate-neutral urban development. The concept contributes to this goal by addressing governance, implementation, and learning environments across the sectors of energy, mobility, and buildings. Geothermal energy is identified as one of several key measures for defossilizing the energy system and supporting the transition to climate neutrality.

Effectiveness and Identified Gaps in Groundwater Thermal Use Management

Technical and Analytical Tools

- **Effectiveness**:
  - The use of ÖWAV-Regelblatt 207 (more information in D.1.3.1) ensures systematic environmental impact assessments for geothermal installations. The employed analytical methods provide a basic level of compliance with local standards. However, the lack of integration with advanced GIS systems limits visualization and decision-making capabilities. Additionally, the absence of high-resolution groundwater temperature maps and detailed potential mapping restricts the identification of optimal locations for new installations and the optimization of existing ones.
- **Gaps and Requirements**:
  - High-Resolution Groundwater Temperature Maps: The city lacks detailed temperature maps that can identify thermal hotspots and support geothermal planning. Developing these maps is essential for improving the spatial resolution and coverage of geothermal potential analyses.
  - Detailed Potential Mapping: Current potential maps for thermal use are insufficient in spatial resolution and coverage. Enhanced mapping is required to identify suitable locations for installations and optimize resource use. First explorations indicate medium potential in the Bohemian Massif region due to elevated temperatures and granite or granite-like rocks. Exploring the potential, particularly deep geothermal energy, could also support the transition to a defossilized energy transition.

   - Long-Term Thermal Impact Monitoring: There is no systematic framework for monitoring the long-term thermal impacts of geothermal installations. This gap limits the ability to assess cumulative effects and ensure sustainable use of groundwater resources.
   - Integration of Analytical Tools with GIS Systems: The current reliance on Excel-based calculations for thermal plume modelling should be replaced or supplemented with GIS-based tools to improve visualization and decision-making.

Strategic and Policy Frameworks

- **Effectiveness**:
   - The permitting and monitoring framework for geothermal installations ensures compliance with local and regional regulations. However, geothermal use is not yet fully integrated into Linz's broader renewable energy and climate adaptation strategies, reducing its potential contribution to the city's sustainability and resilience goals.
   - The city-wide Climate Neutral Industrial City Linz 2040 (2024) for net-zero greenhouse gas emissions and sustainable carbon management provides a solid and comprehensive framework for climate change adaptation. A geothermal potential mapping is mentioned and recommended.
- **Gaps and Requirements**:
   - Cumulative Impact Assessment Framework: The city lacks a framework for assessing the cumulative thermal impacts of multiple geothermal installations. Developing such a framework is critical to prevent conflicts and ensure the sustainable use of groundwater resources.
   - Strategic Alignment with Broader Urban Planning Goals: Geothermal energy planning should be strategically aligned with urban development and climate adaptation goals (1st Linz Climate Strategy 2019) to maximize its contribution to the city's long-term sustainability.

Groundwater Quality

Existing Strategies and Measures

Technical and Analytical Tools

- Groundwater quality monitoring in Linz is conducted by Linz AG and Land Oberösterreich (OÖ), particularly in drinking water protection zones. These efforts are complemented by the national groundwater quality monitoring program (GZÜV, more information in D.1.3.1), which provides a broader framework for assessing groundwater quality trends and compliance with national and EU standards. Additionally, industrial sites, including areas with historical contamination, are subject to monitoring and control measures to mitigate the impact of point source pollution on groundwater quality.

Strategic and Policy Frameworks

- Upper Austria's Drinking Water Future (2005): This federal strategy addresses contamination risks by implementing remediation programs in polluted regions and ensuring compliance with technical standards for water infrastructure

- Upper Austria's Pesticide strategy (2023): This federal strategy aims to protect groundwater and surface water quality by reducing the use of problematic pesticides and their metabolites. It emphasizes integrated pest management, erosion control, and monitoring, while promoting collaboration between agriculture and water management authorities to ensure sustainable water resources for future generations.

Effectiveness and Identified Gaps in Groundwater Quality

Technical and Analytical Tools

- **Effectiveness**:
  - The monitoring systems in Linz, supported by Linz AG, Land OÖ, and the national GZÜV program, provide a robust framework for assessing groundwater quality trends and ensuring compliance with EU standards. Point source pollution control measures, particularly in industrial areas, have been effective in mitigating localized contamination. However, the spatial coverage of the monitoring network is limited, especially outside drinking water protection zones, which restricts the ability to capture a comprehensive picture of groundwater quality. The increasing use of road salt and subsequent infiltration into shallow groundwater poses a problem for drinking water production.

- **Gaps and Requirements**:
  - Spatial Coverage of Monitoring Network: The existing monitoring network does not provide comprehensive spatial coverage, particularly in areas outside drinking water protection zones. Expanding the network is necessary to capture a more complete picture of groundwater quality in the city of Linz.
  - The absence of centralized, digital data management systems (e.g., metadata catalogue) for groundwater quality reduces the efficiency of data sharing and decision-making among stakeholders.
  - In the past, drinking water supply systems near the Danube have experienced more frequent and intense extreme water events, which has led to the deterioration of groundwater quality due to microbial contamination. Linz AG is searching for suitable microbial monitoring tools to ensure the production of clean drinking water during extreme weather events.

Strategic and Policy Frameworks

- **Effectiveness**:
  - Federal strategies such as Upper Austria's Drinking Water Future. (2005) and Upper Austria's Pesticide Strategy (2023) have been instrumental in addressing contamination risks and promoting sustainable water management practices. Local measures, including wellhead protection zones and land use restrictions, have effectively safeguarded drinking water sources.
- **Gaps and Requirements**:
  - A strategic framework is required to coordinate the application of existing tools and methods for managing urban diffusive pollution caused by road salt application. This framework should focus on effectively identifying, tracking, and regulating pollution sources through better integration and implementation efforts.
  - Stakeholder Engagement Mechanisms: Improved collaboration between city departments, regional authorities, and other stakeholders is needed to streamline groundwater quality management efforts and ensure consistent data sharing.

Groundwater Ecosystems

Existing Strategies and Measures

Technical and Analytical Tools

While monitoring systems exist for groundwater quality, there are no specific protocols in place for assessing groundwater ecosystems, including biodiversity and ecological functioning.

Strategic and Policy Frameworks

- European Green City Accord (2020) This is currently the only strategy which could acknowledge the ecological aspects and thereby the organisms associated to groundwater as a habitat. The Green City Accord was adopted in spring 2023 for the city of Linz. It measures progress relative to the policy goals in the EU Biodiversity Strategy for 2030 (2020).

Effectiveness and Identified Gaps in Groundwater Thermal Use Management

Technical and Analytical Tools

- **Effectiveness**:
    - The absence of specific monitoring protocols for groundwater ecosystems limits the ability to assess and manage biodiversity and ecological functioning. While general groundwater quality monitoring systems are in place, they do not address the unique requirements of ecosystem management, such as species inventory or habitat assessment.
- **Gaps and Requirements**:
    - Characterization: There is no information on groundwater ecosystems or biodiversity in the Linz area. Mapping and characterizing these ecosystems are essential for understanding their current state and planning conservation measures.
    - Species Inventory and Habitat Assessment: A comprehensive inventory of species and an assessment of their habitats are required to evaluate the ecological health of local aquifer systems.
    - Ecological Functioning Analysis: There is a need for studies to analyze the ecological functioning of groundwater systems to ensure their sustainability and resilience.

Strategic and Policy Frameworks

- **Effectiveness**:
    - The adoption of the European Green City Accord demonstrates a commitment to integrating ecological considerations into urban

planning. However, the lack of specific measures or data on groundwater ecosystems in Linz limits the effectiveness of this strategy in addressing biodiversity and ecological health.

- **Gaps and Requirements**:
    - Local Protection Criteria and Targets: After an initial description and characterization of groundwater species and habitats in the pilot city Linz, it will be necessary to establish local protection criteria and targets to safeguard the area's biodiversity.

Ljubljana

Groundwater Quantity

Existing Strategies and Measures

Technical and Analytical Tools:

- Available time series of water-table data (with records dating back to 1973) from around 50 monitoring stations located at Ljubljansko polje and 24 stations located at Ljubljansko barje. 18 active stations are located inside Municipality of Ljubljana (Archive of Groundwater data of Slovenian Environment Agency (https://vode.arso.gov.si/hidarhiv/pod_arhiv_tab.php).

- Data on groundwater level, temperature and electro-conductivity (daily resolution) from 8 monitoring stations in the city area are available on web viewer of Slovenian Environment Agency (https://www.arso.gov.si/vode/podatki/podzem_amp/).

- An expert system to support the decision-making process for the management of alluvial groundwater bodies. The system links numerical groundwater flow models with water permit and concession databases to help groundwater managers quantify the availability of groundwater for a given body and provide additional information about the quantity of groundwater for water rights licensing. (Slovenian Environment Agency), https://meteo.arso.gov.si/met/sl/watercycle/bober-ens/).

- 3D numerical groundwater models used to simulate groundwater flow and solute transport (https://www.mdpi.com/2073-4441/12/4/1171).

Strategic and Policy Frameworks:

- Sustainable Urban Strategy of the City Municipality of Ljubljana 2014–2030: The strategy integrates groundwater protection into urban planning and spatial development policies, promotes sustainable water supply from local aquifers with minimal treatment, encourages natural infiltration and retention of rainwater to support aquifer recharge, introduces green infrastructure (e.g., permeable surfaces, rain gardens) to reduce runoff and support groundwater sustainability and integrates climate change adaptation measures to secure long-term groundwater availability.

- Decree on the Status of Groundwater (2022–2027): Decree defines quantitative and chemical status objectives for all groundwater bodies in

Slovenia in line with the EU Water Framework Directive. It defines the methods and criteria for its assessment.

Effectiveness and Identified Gaps in Groundwater Quantity

- **Effectiveness:**
    - The monitoring networks provide systematically collected data and a basis for interpreting the quantitative status of groundwater.
    - Analytical tools support the interpretation of groundwater conditions and decisions relating to the management of this water resource.
- **Gaps and Requirements:**
    - The monitoring networks are not integrated into a single system and data are only partly publicly available.
    - Public discussion and stakeholder engagement in planning and implementing facilities and infrastructure that could potentially impact groundwater are not well established.

Groundwater Thermal Use

Existing Strategies and Measures

Technical and Analytical Tools:

- A web portal (GeoPLASMA-CE, 2025) providing comprehensive information on geothermal potential with associated possibilities and regulatory or technical constraints for the implementation of geothermal systems.
- Guideline for installing geothermal systems and procedures for obtaining water rights for the thermal use of groundwater are established on national level (Prestor et al., 2021).
- The web application (Water Atlas, 2025) provides an interactive platform for accessing spatial data and information on water permits for the thermal use of groundwater and the maximum permitted pumping rate, as well as permit expiry dates.

Strategic and Policy Frameworks

- LEK-MOL (Local energy plan – MOL) - It includes measures for diversifying energy sources, including shallow geothermal energy. These measures are planned for the period 2024–2030 and include: preparing expert bases for displaying geothermal potential; creating a digital spatial layer to present heating demand; determining bivalent heating options in district heating systems; promoting the successful implementation of shallow geothermal installations; creating a groundwater temperature map; establishing a geothermal database; and establishing cooperation with decision-makers.

- Mission 100 – Climate Neutral & Smart Cities
    - Pilot for sustainable urban heating: Within the EU Mission 100 framework, Ljubljana is piloting innovative heating solutions, including shallow geothermal systems and heat pumps, to reduce emissions from buildings and public infrastructure.
    - Decarbonization through geothermal energy integration: Under the “energy systems” pillar of Ljubljana’s Climate City Contract, shallow geothermal energy is explored as part of the strategy to decarbonize heat supply, boost green energy production, and enhance energy efficiency.

Effectiveness and Identified Gaps in GW Thermal use

Technical and Analytical Tools:

- **Effectiveness**:
    - Information accessible via web applications provides an easy and user-friendly way to access spatial information on geothermal potential (possibilities and limitations of geothermal energy use) and water permits granted for the thermal use of groundwater.
    - Guidelines for the implementation of shallow geothermal systems provide a procedural framework and recommendations for the implementation of geothermal systems.
- **Gaps and Requirements:**
    - Groundwater temperature monitoring: The temperature of groundwater has not been systematically measured in the past. The spatial coverage of measurements and short time series strongly limit interpretation of impacts of operating geothermal systems, which is needed for the planning of new geothermal use.
    - Geothermal installations monitoring: Limited availability of operational monitoring data of geothermal systems. The maximum permitted abstraction volume (available information from permits)

does not realistically reflect the actual use of groundwater or its temporal profile.

- Decision support tools: Currently, no numerical tools are used in the planning and permitting procedure, which would enable the simulation of the thermal impact of geothermal installations and their cumulative impact on groundwater. Such tools would support the planning process and ensuring more efficient and sustainable use of groundwater and reducing conflict between users.

Strategic and Policy Frameworks:

- **Effectiveness**:
  - Strategic documents recognise geothermal energy as an important source of renewable energy.
- **Gaps and Requirements:**
  - Long duration of procedures for acquiring water permits for thermal use of groundwater.
  - The role of geothermal energy in the city's energy supply, as outlined in the strategic documents, is not fully aligned with the action plans.

Groundwater Quality

Existing Strategies and Measures

Technical and Analytical Tools

- Operational monitoring of groundwater quality since 1997 (JP VOKA SNAGA-Water supply company)
  - 14 locations (6 wells for drinking water supply + observation boreholes)
- 2025 Monitoring Programme – Assessment of Groundwater Chemical Status (Program monitoringa za leto 2025 – Kemijsko stanje podzemne vode)
- Department of Environmental Protection is responsible for monthly monitoring of industrial and water-supply wells – publicly available yearly reports
- Slovenian Environment Agency release yearly reports on chemical status of groundwater in Slovenia.

- A decision support system for emergency response to groundwater resource pollution in an urban area of Ljubljana (https://link.springer.com/article/10.1007/s12665-014-3662-2).

Strategic and Policy Frameworks

- Sustainable Urban Strategy of the City Municipality of Ljubljana 2014–2030 (Trajnostna urbana strategija MOL 2014-2030)

    - Protection of groundwater sources is encouraged through strict land-use planning that minimizes contamination risks from industrial, agricultural, and urban activities.
    - The implementation of sustainable stormwater management systems is encouraged to reduce pollutant infiltration into aquifers.
    - Regular monitoring and assessment of groundwater quality is encouraged to ensure compliance with national and EU water directives.
    - The integration of climate change adaptation measures is encouraged to protect groundwater resources from extreme weather events and altered recharge patterns.

- Regulation on Drinking Water Supply (*Official Gazette of the Republic of Slovenia* (Nos. 88/12, 44/22 – Environmental Protection Act, 70/24, and 21/25))
- Municipal Spatial Plan Ordinance for the City of Ljubljana.
    - Maintaining groundwater quality through improved coverage of sewage systems and reduction of losses from water supply networks.
    - Groundwater quality monitoring.

Effectiveness and Identified Gaps in GW quality

Technical and Analytical Tools:

Effectiveness

- The water quality and temperature are regularly monitored by MOL and VOKA (municipality level) and by ARSO (national level).
- The developed tools provide efficient support for the interpretation of pollution transport, the identification of its source, and the planning of mitigation measures.

Gaps

- Monitoring data are collected and maintained separately by different institutions (Slovenian Environment Agency, city departments, and the water supply company).

Groundwater Ecosystems

Existing Strategies and Measures

Technical and Analytical Tools

- In Ljubljana, there is currently no monitoring of the ecological status of groundwater, and only the following parameters are measured to assess its quality: physico-chemical parameters, mineral oils, halogen compounds, pesticides, halogenated hydrocarbons, and chromium. At the national level, ecological monitoring of groundwater status is also not required; the only incentive for its development is the European Biodiversity Strategy 2030.

Strategic and Policy Frameworks

- *Water Framework Directive (WFD – 2000/60/EC)*
  Requires that groundwater quality and quantity be managed to prevent significant damage to terrestrial ecosystems, including Natura 2000 sites.
  Groundwater bodies must achieve good quantitative and chemical status, particularly to protect ecosystems that depend on them.
- *Habitats Directive (92/43/EEC)*
  Natura 2000 is founded on this directive, which requires the protection of natural habitats and species listed in its annexes.
  Many habitats (e.g. wetlands, alluvial forests, bogs) and species (e.g. amphibians, invertebrates) are groundwater dependent.
  Failure to adequately manage groundwater may result in deterioration of Natura 2000 sites, constituting a legal violation of the Habitats Directive.
- *Water Management Plans (NUV 2022–2027)*
  Groundwater-dependent ecosystems are identified and mapped.
  In Slovenia, 20 Natura 2000 sites have been recognised as groundwater dependent.
- *Environmental Impact Assessments (EIA/SEA)*
  Any planned water abstraction, construction, or land use change must assess potential impacts of groundwater alterations on Natura 2000 sites.

Effectiveness and Identified Gaps in Groundwater Ecosystem Management

Technical and Analytical Tools

- **Effectiveness**:
  Due to the lack of protocols and legally mandated monitoring, groundwater ecosystems are not assessed or observed for changes.
- **Gaps and Requirements**:
  Some data on groundwater fauna are available from scientific studies, but these data are limited and do not represent the entire Ljubljansko polje aquifer. Further research on groundwater communities and ecosystems, as well as the development of a shared, accessible database, is needed to establish functional ecosystem-based monitoring.

Strategic and Policy Frameworks

- **Effectiveness**:
  The City of Ljubljana has no legal framework requiring ecosystem or biodiversity studies and the monitoring of groundwater ecosystems. Consequently, ecosystem-based monitoring is missing.
- **Gaps and Requirements**:
  Despite the importance of groundwater ecosystems, they are not included in monitoring and are in Slovenia (Ljubljana) generally overlooked in all directives and laws (which only highlight the importance of groundwater for groundwater-dependent habitats). It is therefore essential to develop a methodology for the assessment of groundwater ecosystems and to establish legislation that, in evaluating groundwater status, also incorporates the condition of groundwater ecosystems.

Milan

Groundwater Quantity

Groundwater levels in the Milan area have experienced significant fluctuations over recent decades, driven by both human activities and climate variability. A notable rebound in groundwater levels has been observed following the decommissioning of numerous industrial facilities (starting from 1970) that had previously extracted large volumes of groundwater (around 1950).

The most critical issues have occurred during periods of intense precipitation (e.g., in 2015 and 2024), when rising groundwater levels flooded underground structures such as building basements, metro stations, and tunnels.

A city-wide strategy is still lacking—one that integrates continuous monitoring of groundwater levels, identification of at-risk structures, assessment of future flood risks, and evaluation of the effectiveness of current mitigation strategies, including adjustments to groundwater level control wells.

Existing Strategies and Measures

Technical and Analytical Tools:

- Groundwater monitoring by the Integrated Water Service Provider (MM spa) at municipal level (City of Milan) through ~90 piezometers distributed across the city. Semestral piezometric maps are available at their website.
- Groundwater monitoring by the Integrated Water Service Provider (Gruppo CAP) at provincial level (Metropolitan City of Milan). Geoportal showing the location of existing wells and piezometers and associated groundwater level measurements if available. Groundwater levels are available only in the online viewer tool.
- Active groundwater compensation system: ~93 shallow wells are used to mitigate rising trends in specific zones. These wells are managed by the Municipality of Milan (PP) and MM s.p.a.
- 3D numerical groundwater models are used to simulate subsurface flows and interactions with urban infrastructure (research paper, research paper)
- Data-driven time series analysis (95 wells, 2005–2019) using statistical tools to identify critical zones and define four management areas (research paper)

Strategic and Policy Frameworks:

- The water protection and use plan (PTUA) is a regional technical guideline that analyses the status of groundwater, define the geometry and characteristics of groundwater bodies and gives technical attachments for the use of groundwater in compliance with the regulation and sustainability principles.

- Groundwater themes are also integrated into City spatial and urban planning tools such as the Territorial Plan and PGT (Municipal Zoning Plan), connected with civil protection, water quality, and infrastructure planning (PTUA regional plan).
- Municipal technical regulations (PUGSS and PTUS) govern underground urban development, using data and mapping to coordinate construction and protect against groundwater risks.
- Program Agreement (since 1999) between the Lombardy Region, Milan Municipality (PP), and Po River Basin Authority to control groundwater level rise.

Effectiveness and Identified Gaps

Technical and Analytical Tools:

- **Effectiveness**:
    - Groundwater control wells successfully protected specific underground structures during the extreme rising events of 2015 and 2024. However, limited data collection, changes in local conditions, and overlapping effects hinder the ability to evaluate the effectiveness of individual measures.
- **Gaps and Requirements**:
    - Groundwater level monitoring: currently, the spatial and temporal resolution of groundwater level monitoring is insufficient to analyze the frequency and spatial distribution of groundwater extremes. More frequent—or ideally continuous—measurements are needed to accurately assess groundwater fluctuations and their underlying causes. In recent years, the situation has worsened, as many monitoring wells are either no longer measured or monitored only sporadically, largely due to the absence of a centralized monitoring strategy.
    - Survey of underground structures: the subsurface extent of underground structures is poorly documented and not systematically organized, for example in a 3D model or database of subsurface infrastructure. Developing such a resource, combined with historical monitoring data, would support risk analyses and help identify the most vulnerable structures.

- Specific monitoring: underground structures most vulnerable to rising groundwater should be supported by a dedicated monitoring plan, enabling stepwise mitigation procedures (such as the use of control wells)
- Groundwater extraction: although the amount of extracted groundwater is recorded during the authorization process, there is no subsequent monitoring of actual groundwater usage to enable accurate hydrogeological balance studies.
- Groundwater recharge: in urban areas, the groundwater recharge process is highly approximate, both in estimating the available unsealed areas for recharge and in assessing secondary sources, such as leakage from surface water bodies or water infrastructure. This uncertainty limits the accurate calculation of groundwater balance and hinders studies aimed at identifying measures to prevent excessive groundwater rise or depletion.

Strategic and Policy Frameworks:

- **Effectiveness**:
  - Numerous studies have highlighted the interactions between groundwater and underground structures, and some of these aspects have already been incorporated into territorial planning instruments (PGT) for future infrastructures and buildings
- **Gaps and Requirements**:
  - Groundwater fluctuations risk analysis: the city lacks a detailed risk assessment of groundwater fluctuations, largely due to the limited availability of historical groundwater level data and the absence of a comprehensive dataset of vulnerable underground structures. Several facilities are at risk from high water tables, highlighting the need to update existing building guidelines and to strengthen their coordination with groundwater risk maps
  - Institutional gaps: fragmented stakeholder coordination and delays in the implementation of both structural and non-structural measures.

Groundwater Thermal Use

Recent EU directives and local policies have encouraged the development of shallow geothermal energy as a renewable, low-emission source. Milan is in a very prone area with a high potential for thermal use of shallow groundwater. Therefore, it is experiencing a strong growth in the application of this technology for heating/cooling. On the other hand, the high built-up density and associated energy demand is fostering a rapid development of shallow geothermal applications which require appropriate tools to monitor and model the associated effects on both the quality and quantity of the available resource.

Existing Strategies and Measures

Technical and Analytical Tools:

- A webgis is updated by *Città Metropolitana di Milano* showing the existing (authorized) Groundwater Heat Pump (GWHP) systems. It includes the location of extraction and reinjection wells, their depth, the mean annual discharge and the peak discharge. Another dataset is maintained by Regione Lombardia showing the location and characteristics of Ground Source Heat Pumps (GSHP).
- Environmental Impact Assessment Procedures: The environmental impact of geothermal installations is assessed following the regional technical regulation (No. X/6203 – 08/02/2017 see D.1.3.), which provides comprehensive technical guidance and requirements (such as analysis of the impacts) to receive the authorization for groundwater thermal use and reinjection. The methodology for assessing the sustainability and impacts of the proposed system is upon the proposer.
- Groundwater modelling: 3D numerical models including heat transport and groundwater flow are used to assess the sustainability and cumulative impacts of geothermal systems during the environmental assessment proceure.
- City scale 3D model: developed by Unimib (PP) to analyze cumulative impacts of GWHP systems and the development of the Subsurface Urban Heat Island (SUHI) in the Milan city. This comprehensive model is calibrated with real groundwater temperature and level data.

Strategic and Policy Frameworks:

- A periodic report (every two years) is issued by Città Metropolitana di Milano describing the growth of GWHP (only number on wells and systems and their spatial distribution)

- Milan Municipality (Comune di Milano, PP) and the Milan Metropolitan City (Città Metropolitana di Milano) have set goals on the development of local renewable energy resources through their respective policy frameworks: the Climate and Air Plan from the Milan Municipality, and the redaction of Guidelines for the energy transition from the Milan Metropolitan City. Both actions include the use and optimization of the geothermal use of groundwater.
- In March 2024, the City of Milan, the Metropolitan City, and the University of Milano-Bicocca signed a formal agreement to promote the sustainable development of urban geothermal systems. The agreement provides for data sharing, technical collaboration, and the design of an operational model (still under development) for hydro-geothermal management, aimed at assessing and preventing system interactions in densely built urban areas.

Effectiveness and Identified Gaps

Technical and Analytical Tools

- **Effectiveness**:
  - The environmental impact assessment procedure for geothermal installations assures a system-scale comprehensive evaluation meeting the actual regulation on groundwater use. However, the lack of data collection limits comprehensive city-scale evaluations, visualization and decision-making capabilities.
  - Potential mapping throughout analytical and numerical tools is very effective for resource optimization but remains so far poorly implemented on a city-scale level.
  - Additionally, the absence of high-resolution groundwater temperature maps and detailed potential mapping restricts the identification of optimal locations for new installations and the optimization of existing ones.
- **Gaps and Requirements**:
  - Groundwater temperature monitoring: The city lacks detailed groundwater temperature maps that can identify hotspots. This absence limits the identification of heating or cooling prone areas and brings to wrong estimations of the groundwater thermal potential which is related to the temperature limits for groundwater reinjection.

- Groundwater thermal potential: A detailed groundwater thermal potential analysis is still lacking (available only from research studies). A thermal potential mapping is required to identify suitable locations for installations and optimize resource use.
- Spatial coordination and sustainability assessment: The city and the respective authority for groundwater lack tools for assessing the cumulative thermal impacts of multiple geothermal installations. Developing such a framework in densely built areas is critical to prevent conflicts among users, ensure the sustainable use of the resource and maximize the extractable thermal potential. No current tool ensures proper spacing between installations, leading to system interference and reduced long-term efficiency. There's a need for updated rules on thermal load sharing and buffer zones.
- Geothermal installations monitoring: There is no monitoring for groundwater and thermal energy used by the geothermal wells. This limits the capability to make comprehensive and long-term city-scale analysis and forecasts on the exploitation of the groundwater thermal resource.
- Inconsistent reinjection practices: Some GWHP systems discharge groundwater to surface or canals instead of reinjection into the same aquifer, disrupting the hydrogeological balance. However, systems discharging back into groundwater increase thermal stress. There is a need for coordination.
- GIS systems: The above proposed tools should be integrated in a GIS-based tool to improve the visualization and decision-making about shallow geothermal resource in the urban area. This would be beneficial for urban planners to optimize the extraction of groundwater-based thermal energy but also for proposer to better design the systems in a sustainable way.

Strategic and Policy Frameworks

- **Effectiveness**:
  - Urban geothermal systems already supply up to 20% of Milan's metropolitan heating demand, with significant potential to reduce CO_2 emissions and contribute to the city's energy transition goals.

    - The integration of geothermal energy into local policies has a high effectiveness in promoting and fostering the development. However, there is a strong need to support this development with appropriate tools to manage the exploitation.

- **Gaps and Requirements**:
    - Coupling energy demand with geothermal resource availability: Geothermal energy planning should be aligned with the local energy demand. A priority scale for users should be identified to avoid a “first come, first served” approach. This would maximize the energy extraction and guarantee city's long-term sustainability.

Groundwater Quality

Existing Strategies and Measures

Milan follows the European Union’s Water Framework Directive (WFD) and the Groundwater Directive (2006/118/EC), which provide a legal framework to monitor and protect groundwater from pollution.

Technical and Analytical Tools:

- AMIIGA – Interreg Central Europe Project, Pilot Action 3: AMIIGA enabled the implementation of tools to distinguish point sources of pollution from diffuse contamination, the development of a set of measures and the Management plan, to monitor and manage pollution and prevent further groundwater contamination.
- The PLUMES Project in Lombardy Region, launched in 2012, investigated groundwater contamination plumes in Lombardy to identify potential pollution sources and support remediation and safety measures. Activities included groundwater monitoring, and mathematical modelling to characterize complex contamination and assess risks to sensitive receptors.
- Natural background concentration values for underground water bodies, as a basis for distinguishing anthropogenic contamination from naturally occurring levels.
- Vulnerability mapping tools using Weights of Evidence and Logistic Regression have been developed to identify susceptibility to contaminants such as PCE (Perchloroethylene), TCE (Trichloroethylene), Hexavalent Chromium, Nitrates, especially in peri-urban areas (Istituto per la Dinamica dei Processi Ambientali IDPA and the Istituto di Geologia Ambientale e Geoingegneria IGAG, 2005).

Strategic and Policy Frameworks

- Milan's Urban Development Plan (PGT 2019) incorporates groundwater protection by regulating land use and limiting activities that risk aquifer contamination, especially in areas of shallow water tables.
- Water Safety Plans (WSP), aligned with EU and WHO standards, have been adopted in Milan to ensure the safety of urban drinking water, using risk-based management approaches for contamination prevention across the entire supply chain.

Effectiveness and Identified Gaps in Groundwater Quality

- **Effectiveness**
  - Technical tools like numerical models and statistical analyses have successfully identified contamination hotspots, supporting targeted mitigation and resource planning.
- **Gaps and Requirements**:
  - Uncertainty in deeper aquifer pollution: deeper confined aquifers (e.g., intermediate and deep aquifer systems) lack detailed quality mapping due to limited access and data.
  - Policy fragmentation: groundwater quality responsibilities are split among municipal, regional, and utility agencies, limiting coordinated action.
  - Limited public reporting: Groundwater quality data is often not fully transparent or accessible to citizens or civil society.

Groundwater Ecosystems

Existing Strategies and Measures

Technical and Analytical Tools:

There is often a lack of expertise on this topic to establish a management of groundwater ecology. There are no specific actions related to the groundwater fauna monitoring.

Strategic and Policy Frameworks:

No specific strategies in place that deal with groundwater ecosystem management. Often groundwater ecosystems are included in topics of groundwater quality or biodiversity in water in general.

Effectiveness and Identified Gaps

There has been limited assessment of chemical and microbiological impacts. Considering the changes in the groundwater thermal regime driven by urbanization and climate change, it is necessary to evaluate whether thermal changes influence groundwater chemistry or microbiota.

Munich

Groundwater Quantity

Existing Strategies and Measures

Technical and Analytical Tools:

- Continuous groundwater monitoring network with over 2000 observation wells. Water levels at these observation wells are usually measured weekly or every 2 weeks with an electric contact gauge. Measurements are taken more frequently while securing evidence on municipal buildings or civil engineering structures. A portion of the wells are equipped with data loggers measuring water levels and temperatures hourly or every 4 to 6 hours. The number of data loggers is constantly increased. Some data loggers are equipped with a telemetry system for "real-time" (one or twice a day) data upload. Data is stored in a database that is shared between city departments.
- Update of the maximum groundwater level map (currently ongoing)
- Investigation/Modelling of Changes in Groundwater Levels due to Anthropogenic and Natural Factors (study, currently ongoing)
- A potential map for infiltration is in progress

Strategic and Policy Frameworks:

- Nationale Wasserstrategie (National Water Strategy)
- Bayerische Klima-Anpassungsstrategie 2016 (Bavarian Climate Adaptation Strategy 2016)
- Wasserentnahme Gebühr – Wassercent (Water Extraction Fee – Watercent) starting 2026
- Wasserzukunft Bayern 2050 (Water Future Bavaria 2050)
- Deutsche Anpassungsstrategie an den Klimawandel (German Climatechange Adaptation Strategy)
- Konzept zur Anpassung an die Folgen des Klimawandels in der Landeshauptstadt München 2016 (Concept for the Adaptation to the Consequences of Climatechange in the City of Munich 2016)
- Klimaanpassung in München – Fortschreibung des Klimaanpassungskonzepts I (Climate Adaptation in Munich – Continuation of the Climate Adaptation Concept I)
- Klimastrategie 2021 – Grundsatzbeschluss I und II (Climate Strategy 2021 – Decision Bill I and II)

- Klimafahrplan – Klimaneutrales München bis 2035 (Roadmap climate – Climate-neutral Munich until 2035)
- „Grüne Stadt der Zukunft“ (Green City of the Future)
- Stadtentwicklungsplan 2040 (City Development plan 2040)
- Klimaresilientes München 2050 (Climate-resiliant Munich 2050
- Merkblatt Bauvorhaben im Grundwasser (Information sheet for construction projects in groundwater)

Effectiveness and Identified Gaps in Groundwater Quantity

Technical and Analytical Tools

- **Effectiveness**:
  - Long-term monitoring of groundwater data is a useful tool to assess the groundwater situation and trend. With over 2000 active observation wells, the groundwater situation in Munich can be mapped adequately. Storing all datasets in a shared database enables access to all relevant stakeholders.
  - The “Update of the maximum groundwater level map” and the “Investigation/Modelling of Changes in Groundwater Levels due to Anthropogenic and Natural Factors” are part of the climate adaptation strategy and are currently being developed.
- **Gaps and Requirements**:
  - While there is an extensive groundwater monitoring network (>2000 active observation wells), this data is not being used for predictive modelling of the expected development of the groundwater situation in Munich.
  - Measurement cycles do not allow to use groundwater data for a warning system regarding groundwater extremes. Munich has started equipping selected observation wells with dataloggers capable of remote data transmission to implement near real-time groundwater data.
  - There is a lack of GIS data for infiltration measures and only older groundwater recharge models.
  - Data for securing evidence from third parties is often only sent to the Water Management Office (WWA) and not to the city departments.
  - Different databases between the City of Munich and the Munich Water Management Office (WWA).

Strategic and Policy Frameworks

- **Effectiveness**:
  - Existing strategies on a municipal level prioritise climate adaptation strategies. In the context of groundwater, sponge city concepts are implemented in urban development planning and improvements in existing neighbourhoods.
  - Water extraction contribution for private households, companies and agriculture which is appropriated for water protection and sustainable water management (introduction in 2026).
  - Munich's drinking water is extracted primarily from the Mangfall and Loisach valleys. The Munich gravel plain serves as a reserve source. Munich's municipal utilities (SWM) ensure the drinking water supply through a combination of these three extraction areas.
  - In construction projects in Munich, great importance is placed on minimizing the impact on the groundwater situation. This is achieved through various measures that are already taken into account during the planning phase.
- **Gaps and Requirements**:
  - Given the abundance of groundwater in Munich, no specific strategies are in place to protect groundwater quantity. However, groundwater recharge is being improved through the implementation of sponge city concepts and nature-based rainwater management.
  - From 2026, implementation of a water extraction fee with a free allowance of 5000 m^3. However, real extraction quantities are often not assessed.

Groundwater Thermal Use

Existing Strategies and Measures

Technical and Analytical Tools

- GEO.KW to enhance the efficiency of thermal groundwater use in urban areas by developing a flexible planning and optimization tool. This tool enables urban heating and cooling demands to leverage the dynamics and storage capacity of thermal groundwater, increasing the use of renewable energy and reducing primary energy consumption. Specifically, replacing conventional cooling systems with groundwater-based free cooling will help lower greenhouse gas emissions. The objective will be achieved through detailed simulations of groundwater flow and heat transport combined with an energy systems optimization tool.

- Thermal use database recording the type of use, approved withdrawal, and temperature spread are recorded.
- Shared database of groundwater temperature measurements.
- Maps of groundwater temperature based on key date measurements of groundwater temperature throughout the city.
- Maps of the shallow geothermal potential including groundwater depth, groundwater thickness, heat capacity and technically feasible extraction rates.
- Measuring network of groundwater temperature with currently ~90 observation wells. This measuring network will be expanded to around 300 wells in the next two years.
- Seasonal groundwater depth temperature profiles (26 observation wells).

Strategic and Policy Frameworks

- Munich heat plan considers the current heat supply in the urban area and provides information on future climate-neutral supply options. An important role is played by the expansion and optimization of heating networks (district heating and local heating). Outside of heating network areas, information is provided on the possibilities for geothermal groundwater use.
- Roadmap climate – Climate-neutral Munich until 2035.

Effectiveness and Identified Gaps in Groundwater Thermal Use Management

Technical and Analytical Tools

- **Effectiveness**:
  - GEO.KW proofed to be a useful tool for the realisation of the geothermal potential in Munich and is currently expanded for the city of Augsburg and Nürnberg.
- **Gaps and Requirements**:
  - The groundwater temperature map was created based on key date measurements in April, as a result these temperatures represent near-minimum temperatures in the annual temperature cycle.
  - Data protection makes it difficult to provide the Geo.KW app for specialist planners and engineers.
  - Different databases between the City of Munich and the Munich Water Management Office (WWA).

Strategic and Policy Frameworks

- **Effectiveness**:
  - Municipal heat planning in Munich offers numerous benefits for citizens, homeowners, and the environment. It creates planning

security for investments in heating systems, promotes the transition to renewable energies, and contributes to reducing CO2 emissions. Homeowners can prepare early for the switch from oil and gas heating and know which heating solutions are best suited to their area.

- **Gaps and Requirements**:
  - Existing private thermal uses are protected by water law. Large district heating networks with well systems can negatively impact these existing wells, which can lead to very strict water law requirements and render the systems unviable.

Groundwater Quality

Existing Strategies and Measures

Technical and Analytical Tools

- Routine water tests of water quality (chemistry and pollutants) for few groundwater observation wells by the regional water authority (WWA).
- Monitoring of water quality (chemistry) for contaminated sites and filled gravel pits.
- Occasional water analyses during the implementation of large construction projects, construction water retention or thermal uses.
- Routine water analyses in the Trudering water protection area by the Munich municipal utilities (SWM).
- Monitoring of groundwater temperature at around 90 observation wells. Measurement network for groundwater temperature will be gradually expanded to around 300 observation wells.
- The Munich Water Management Office (WWA) acts as an official technical expert for the city of Munich

Strategic and Policy Frameworks

- Nationale Wasserstrategie (National Water Strategy)
- Wasserzukunft Bayen 2050 (Water Future Bavaria 2050)
- European Directive on the quality of water intended for human consumption (2020/2184)
- Trinkwasserverordnung 2023 (TrinkwV 2023)
- LfU-Merkblatt 3.8/1 "Untersuchung und Bewertung von Altlasten, schädlichen Bodenveränderungen und Gewässerverunreinigungen - Wirkungspfad Boden-Grundwasser.

- Aktionsplan zur Halbierung des chemisch-synthetischen Pflanzenschutzes in Bayern bis 2028 (Plan of Action for halving the use of chemical-synthetical pesticides in Bavaria until 2028).

Effectiveness and Identified Gaps in Groundwater Quality

Technical and Analytical Tools

- **Effectiveness:**
  - Contaminated sites and suspected areas are very well documented in the city of Munich.
- **Gaps and Requirements**:
  - Groundwater chemistry and pollution measurements could be expanded in order to map and visualise quality concerns.
  - Lack of reporting on groundwater quality in the urban area.

Strategic and Policy Frameworks

- **Effectiveness**:
  - No dedicated strategies for the protection of groundwater. However, groundwater quality is indirectly protected by strategies as well as rules and regulation on EU, German federal and Bavarian level (D.1.3.1). This protection is often phrased through a “requirement to improve” or a “no deterioration rule”.
- **Gaps and Requirements**:
  - The simplification of bureaucracy leads to unrecorded inputs of substances into the groundwater (e.g. fertilizer regulations, nitrate).
  - The designation of water protection areas is often associated with lengthy and complicated procedures, which delays protective measures.

Groundwater Ecosystems

Existing Strategies and Measures

Technical and Analytical Tools

- There is not much data available on Munich’s groundwater ecosystem. Occasional scientific studies collected ecosystem data in Munich.
- In the case of individual large-scale thermal uses that heat the groundwater, water law stipulates that the groundwater fauna is also examined.

Strategic and Policy Frameworks

- Biodiversitätsstrategie City of Munich: Handlungsfeld 13: Gewässerschutz und –renaturierung (Biodiversity Strategy City of Munich: Field of Action 13:

Waterbody protection and renaturation) specificially mentions that groundwater ecosystems should remain intact and undisturbed.

- European Green City Accord acknowledges the ecological aspects of groundwater and thereby the organisms associated to groundwater as a habitat. The Green City Accord was adopted by the city of Munich.
- Water protection areas serve to protect groundwater as a vital drinking water resource and habitat. They are essential for protecting groundwater from contamination and pollution and maintaining its natural purification function.
- FFH-Gebiete: Groundwater fauna in Natura 2000 protected areas is an important component of the European Natura 2000 network of protected areas. Natura 2000 protected areas, designated under the Habitats Directive (FFH Directive), serve to protect specific habitat types and species, including groundwater organisms. The Habitats Directive obliges Member States to protect habitats and species of Community interest, which also includes the protection of groundwater fauna.
- Nationale Wasserstrategie (National Water Strategy): Germany's National Water Strategy also includes measures to protect groundwater fauna. This strategy aims to safeguard the quality and quantity of groundwater in the long term and thus also preserve the habitats of groundwater fauna.
- Wasserzukunft Bayern 2050: One focus is on the protection of groundwater ecosystems, which are of great importance as habitats for many specialized species.

Effectiveness and Identified Gaps in Groundwater Ecosystem Management

Technical and Analytical Tools

- **Effectiveness**:
  No specific tools in place.
- **Gaps and Requirements**:
  - There is often a lack of expertise on this topic to establish a management of groundwater ecology.
  - There is no specific, publicly accessible database dedicated exclusively to the groundwater fauna of Bavaria.

Strategic and Policy Frameworks

- **Effectiveness**:
  - Munich is home to several Natura 2000 protected areas. These areas are protected by the European Union's Habitats Directive, which aims to conserve biodiversity, also the groundwater fauna.
- **Gaps and Requirements**:

- No specific strategies in place that deal with groundwater ecosystem management. Often groundwater ecosystems are included in topics of groundwater quality or biodiversity in water in general.

3. Comparison of current strategies and measures

The following section provides an overview and comparison of groundwater sustainability management approaches across the four MARGIN pilot cities. This assessment focuses specifically on groundwater-related strategies and measures without making broader judgements on general climate adaptation efforts.

Groundwater Quantity

Across the four cities groundwater management has become a central concern in adapting to both climate change and urban development pressures. A common strength lies in the progressive establishment of extensive monitoring networks, in the best cases equipped with automated loggers and real-time telemetry. These networks provide long-term datasets that form the backbone of technical assessments and consequent strategies and measures described. Complementary tools such as groundwater fluctuation risk analysis, thematic mapping, 3D numerical groundwater flow models, and groundwater trend analysis have proven highly effective in supporting decision-making. However, comprehensive studies that combines groundwater recharge dynamics and groundwater extraction in urban areas are not fully developed but would be useful to identify effective mitigation and climate change adaption measures. At the same time, recurring gaps appear across cases. Monitoring systems, while extensive, are often fragmented across institutions, lack harmonization, or are not fully integrated into predictive modelling and GIS-based tools. The temporal resolution of measurements is frequently insufficient for early warning systems, leaving cities vulnerable to extremes such as rising groundwater tables and related flooding risks. Critical datasets, particularly on subsurface infrastructure, are often outdated, incomplete, or not systematically maintained, limiting risk assessments. Institutional challenges also emerge, including fragmented responsibilities, inconsistent stakeholder engagement, and limited mechanisms for incorporating scientific results into policy and planning.

Thermal use of Groundwater

Shallow geothermal energy is recognized in all four cities as a key element of decarbonization. Progress is evident in the gradual establishment of technical standards and strategic frameworks, and, in some cases, advanced analytical tools. Geothermal potential mapping, interactive web platforms and environmental impact assessment procedures provide useful information for decision-making purposes. However, the effectiveness of these tools varies: in some cities, they remain Excel-based or are fragmented across different authorities, and integration with GIS and urban planning processes is limited. Recurring gaps appear across all cities. Systematic monitoring of groundwater temperatures is either absent or incomplete. Where observation networks exist, their spatial or temporal coverage is often insufficient to capture cumulative impacts. Critical datasets, such as high-resolution groundwater temperature maps, are missing in most cities. Operational monitoring of geothermal installations is rare, meaning that actual energy use and the long-term impact on groundwater are not well understood. The lack of frameworks for cumulative impact assessment is a central weakness, particularly in densely built urban areas where system interactions can reduce their efficiency and compromise groundwater thermal use sustainability. Responsibilities for permitting, monitoring and planning are often divided among different authorities, resulting in fragmented governance and limited coordination. Data protection and legal safeguards also restrict the accessibility of planning tools and hinder the sharing of operational data. Although strategic frameworks increasingly recognize the role of geothermal energy in decarbonisation, there is inconsistency between policy ambitions and practical implementation. The comparison shows that although the technical foundations are in place, systematic monitoring, harmonized datasets, GIS-integrated planning tools, and frameworks for cumulative impact assessment are still required to achieve more efficient and sustainable thermal use of groundwater in these cities.

Groundwater Quality

Examining the groundwater quality management efforts in the four project cities, several strengths and identified gaps emerge. In all cities there is an awareness for groundwater quality concerns and accordingly there are strategies in place protecting or improving groundwater quality. Furthermore, all cities have monitoring programs dedicated to groundwater quality providing the framework for groundwater quality management. However, all project cities report limitations in their monitoring programs. Most commonly regarding spatial coverage or temporal resolution of measurements. While contaminated sites and water protection areas are usually well covered, city-wide measurements or measurements in deeper aquifers are sparser. On an organisational level, issues like sharing of monitoring data between involved institutions, the lack of coordinated actions due to split responsibilities or administrative barriers that delay protective measures exist. Elaborate numerical models and statistical analyses have successfully been applied to identify and mitigate contamination hotspots. Overall, while each city has established effective monitoring systems, strategic frameworks, and technical tools, common gaps exist across the board. These include the need for improved data integration, the expansion of monitoring networks to cover more areas, real-time monitoring capabilities, and enhanced collaboration among stakeholders. Addressing these gaps through best practices and coordinated efforts will be essential for advancing groundwater management and protection in urban environments.

Groundwater Ecosystems

Across the pilot cities, no dedicated strategies or management frameworks were found that specifically address groundwater ecosystems. Where these ecosystems are considered at all, it is usually indirectly—under broader concerns such as groundwater quality or urban biodiversity. A major barrier to their inclusion in urban groundwater management is the limited awareness, expertise, data, and technical capacity. Currently, all cities lack essential tools—such as methods for ecosystem characterization, species inventories, and habitat assessments—that would be needed to understand the ecological status and potential functions of groundwater ecosystems in an urban context. Without this foundation, it is difficult to evaluate whether, and in what ways, such ecosystems could contribute to sustainable groundwater management efforts. While the direct benefits of groundwater ecosystem management for water quality or supply remain difficult to quantify, these ecosystems may represent an underexplored asset within broader urban biodiversity and resilience strategies. In this context, establishing accessible data on groundwater fauna and ecological functioning would be a key step toward enabling cities to make informed decisions about their protection and potential integration into local sustainability planning.

Cross-City Comparison and Gap Analysis

The analysis reveals both common strengths and persistent gaps across all four dimensions of groundwater sustainability management examined in this study. All pilot cities demonstrate established monitoring networks that provide essential baseline data for groundwater management decisions. These networks, while varying in scope and sophistication, form the technical foundation for most strategies and measures implemented. Additionally, regulatory frameworks at national and EU levels provide consistent policy direction across all cities, particularly regarding water quality standards and environmental protection requirements. Technical tools such as numerical modelling, GIS-based mapping, and environmental impact assessments are utilized across cities, though with varying degrees of integration and effectiveness. Strategic recognition of groundwater's role in climate adaptation and urban sustainability is evident in policy documents across all locations. Despite these foundations, several critical gaps (see also Table 1-4) appear consistently across cities and management dimensions:

- Data Integration and Accessibility: Monitoring data is frequently fragmented across multiple institutions and databases, limiting comprehensive analysis and coordinated decision-making. Real-time data availability remains limited, reducing the capacity for proactive management and early warning systems.
- Predictive and Analytical Capabilities: While monitoring networks exist, their integration into predictive modelling and advanced analytical tools is often insufficient. This limits cities' ability to anticipate and prepare for groundwater-related challenges under changing climate and urban development conditions.
- Institutional Coordination: Responsibilities for groundwater management are typically divided among municipal, regional, and utility authorities, leading to fragmented governance and inconsistent implementation of measures.
- Stakeholder Engagement: Mechanisms for involving diverse stakeholders—including local communities, industry, and agricultural sectors—in groundwater management planning remain underdeveloped across most cities.

Table 1: Comparison of gaps and requirements in existing strategies and measures addressing groundwater quantity risks related to climate change and urbanisation in MARGIN pilot cities.

Identified gaps and requirements regarding the management of Groundwater Quantity	Linz	Ljubljana	Milan	Munich
Technical and Analytical Tools				
Scattered data availability		x	x	
Incomplete public availability of data		x	x	
Limited frequency of monitoring impedes early warning			x	x
Insufficient (GIS) data for infiltration			x	x
Outdated recharge models				x
Integration of available data into advanced systems of analysis for visualization to support decision making	x			
More advanced tools for long term trend analysis needed	x		x	
More advanced tools for predictive modelling needed	x		x	x
Missing tools to handle risk of flooding due to GW rising			x	
Strategic and Policy framework				
Improve mechanisms for engaging stakeholders to enhance the implementation and acceptance of strategic measures	x	x		
No specific strategy to manage groundwater quantity			x	x
Missing coordination between surface water and groundwater hydrology			x	
A framework to monitor real extraction quantities is needed			x	x

Table 2: Comparison of gaps and requirements in existing strategies and measures addressing thermal use of groundwater risks related to climate change and urbanisation in MARGIN pilot cities.

Identified gaps and requirements regarding the management of thermal use of groundwater	**Linz**	**Ljubljana**	**Milan**	**Munich**
Technical and Analytical Tools				
Spatial and temporal coverage of groundwater temperature monitoring is limited		x		x
Operational performance monitoring data from existing systems is limited/poor		x		
High resolution groundwater temperature maps are missing	x	x	x	
Detailed thermal potential mapping needed	x		x	
Integration of available data into analytical tools needs to be improved	x	x	x	
Numerical tools for planning and permitting not available (e.g., inference analysis)		x	x	
Poor standardization of impact assessment of single systems		x	x	
Strategic and Policy framework				
A framework for long-term impact monitoring is missing	x	x	x	x
Cumulative impact assessment framework needed	x	x	x	
Strategic alignment with broader Urban Planning goals could be improved	x	x	x	
Long duration for acquiring permits for thermal use of GW		x		
Coordination of energy demand and geothermal resource availability is missing		x	x	
Missing Priority scale (urban planning strategy)			x	
Research knowledge not yet transferred to decision-making			x	

Data protection impedes availability for specialists				x
Problems with existing large heating networks that are protected by water law. (Urban Planning, Interference)		x		x

Table 3: Comparison of gaps and requirements in existing strategies and measures addressing groundwater quality risks related to climate change and urbanisation in MARGIN pilot cities.

Identified gaps and requirements regarding the management of Groundwater Quality	Linz	Ljubljana	Milan	Munich
Technical and Analytical Tools				
Spatial coverage needs to be improved	x			x
Transparency and public availability of data need to be improved			x	
Missing tools to monitor microbial contamination due to weather extremes	x			x
A centralized database for GW quality is missing	x	x	x	
Visualization of groundwater quality data missing				x
Strategic and Policy framework				
Stakeholder engagement to ensure consistent data sharing needs to be improved	x			
Strategic framework to manage urban diffusive pollution (e.g. road salt application) is missing	x			
Enforcement of water protection zones at the municipal level is inconsistent		x		
Lack of reporting on groundwater quality in the urban area				x
Policy fragmentation between municipal, regional and national authorities limits coordinated actions			x	
Focus on contaminated sites instead of an overall monitoring strategy				x

MARGIN is co-financed by the European Regional Development Fund through the Interreg Alpine Space programme. **See more about MARGIN at www.alpine-space.eu/project/margin.**

Table 4: Comparison of gaps and requirements in existing strategies and measures addressing groundwater ecosystem risks related to climate change and urbanisation in MARGIN pilot cities.

Identified gaps and requirements regarding the management of Groundwater Ecosystems	Linz	Ljubljana	Milan	Munich
Technical and Analytical Tools				
Lack of knowledge on the existence and functionality of groundwater ecosystems	x	x	x	x
Lack of expertise how to monitor groundwater ecosystems	x	x	x	x
Lack of expertise how to evaluate the status of groundwater ecosystems	x	x	x	x
No (public) databases available for groundwater organisms	x	x	x	x
Strategic and Policy framework				
No specific strategies for the protection of groundwater ecosystems	x	x	x	x
Lack of criteria and targets to establish strategies or policy frameworks	x	x	x	x

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4. Conclusion

The findings of the comparison of existing strategies and measures indicate that while foundational elements for groundwater sustainability management exist across the pilot cities, substantial improvements in data integration, institutional coordination, and technical capacity are required. Groundwater Quantity Management shows the strongest technical foundations, with well-established monitoring networks and analytical tools. However, gaps exist in predictive modelling and integration with urban planning processes. Thermal Use of Groundwater reveals significant potential for renewable energy contribution but lacks systematic monitoring of cumulative impacts and operational performance data. The rapid growth in installations outpaces the development of management frameworks. Groundwater Quality Management demonstrates robust regulatory compliance mechanisms but shows limitations in spatial coverage and data sharing between institutions. Emerging challenges such as urban diffuse pollution require enhanced coordination frameworks. Groundwater Ecosystem Management represents the most significant knowledge and capacity gap across all cities, with virtually no dedicated strategies, monitoring protocols, or technical tools in place. The development of harmonized monitoring approaches, integrated planning tools, and stakeholder engagement mechanisms will be essential for advancing effective groundwater sustainability management in Alpine urban areas.

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