



INTER  
STORES

Deliverable

International Innovation Network  
for the Development of  
**Cost- and Environmentally  
Efficient Seasonal Thermal  
Energy Storages**

**D5.4 - Monitoring concepts for sTES  
ambient domains**



Funded by  
the European Union

Project funded by



Schweizerische Eidgenossenschaft  
Confédération suisse  
Confederazione Svizzera  
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs,  
Education and Research EAER  
State Secretariat for Education,  
Research and Innovation SERI

Grant Agreement Number	<b>101136100</b>	Acronym	<b>INTERSTORES</b>	
Full Title	International Innovation Network for the Development of Cost- and Environmentally Efficient Seasonal Thermal Energy Storages			
Start Date	01/01/2024	Duration	48 months	
Call	HORIZON-CL5-2023-D3-01			
Topic	HORIZON-CL5-2023-D3-01-14			
Funding Scheme	Horizon Europe Research and Innovation Programme			
Type of action	HORIZON Innovation Actions			
Project URL	<a href="https://interstores.eu/">https://interstores.eu/</a>			
Social Media	X	<a href="https://twitter.com/InterstoresEU">https://twitter.com/InterstoresEU</a>		
	Flickr	<a href="https://www.flickr.com/people/199918844@N06/">https://www.flickr.com/people/199918844@N06/</a>		
	LinkedIn	<a href="https://www.linkedin.com/showcase/interstores/">https://www.linkedin.com/showcase/interstores/</a>		
	YouTube	<a href="https://www.youtube.com/@InterstoresEU">https://www.youtube.com/@InterstoresEU</a>		
Work Package	WP5 - Environment			
Deliverable	<b>D5.4 – Monitoring concepts for sTES ambient domains</b>			
Deliverable Type	R – Document, report			
Dissemination Level	PU – Public, fully open, e.g., web			
Date of Delivery	Contractual	30/09/2024	Actual	25/09/2024
Lead Beneficiary	Martin Luther University Halle-Wittenberg (MLU)			
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## Document Revision History

Version	Issue Date	Stage	Modified by	Changes
1	02/09/2024	Draft	Bott, Christoph (MLU), Hoffmann, David (MLU), Bayer, Peter (MLU), Vallin, Sami (GTK), Kortunov, Evgenii (GTK), Hagström, Markku (GTK), Siponen, Matias (VNT), Pitkänen, Hanna (VNT),	First draft
2	19/09/2024	1 <sup>st</sup> revision	Hagström, Markku (GTK), Teppo Arola (GTK), Christoph Bott (MLU)	1 <sup>st</sup> revision after feedback by GTK, (WP-related review)
3	20/09/2024	2 <sup>nd</sup> revision	Rainer Strobel (PGM), Emre Bas (PGM), David Hoffmann (MLU)	2 <sup>nd</sup> revision after feedback by PGM (WP-external review)
4	25/09/2024	Coordinator Revision	Peter Bayer (MLU)	Final validation
5	25/09/2024	Submission	Peter Bayer (MLU)	Upload

## INTERSTORES Consortium


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12	WIZ DEVELOPMENT & SERVICES SRL	WIZ	RO	BEN
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\***Role:** COO-Coordinator; BEN-Beneficiary; AE-Affiliated Entity; AP-Associated Partner



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Federal Department of Economic Affairs,  
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State Secretariat for Education,  
Research and Innovation SERI

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### Abbreviations and Acronyms

aDTS	Active Distributed Temperature Sensing
CTES	Cavern Thermal Energy Storage
DAS	Distributed Acoustic Sensing
DTS	Distributed Temperature Sensing
DSS	Distributed Strain Sensing
EC	European Commission
ERT	Electrical Resistivity Tomography
Giga-CTES	Large-scale Cavern Thermal Energy Storage
GPR	Ground-Penetrating Radar
PU	Public
Reno-sTES	Seasonal Thermal Energy Storage at the incampus site
SEN	Sensitive
PTES	Pit Thermal Energy Storage
sTES	Seasonal Thermal Energy Storage
T	Task
TTES	Tank Thermal Energy Storage
WGTES	Water-Gravel Thermal Energy Storage
WP	Work Package



# 1 Introduction

## 1.1 Project overview and motivation

Future energy systems necessitate the integration of diverse, variable renewable energy sources to replace fossil fuels, leverage sector coupling, and recover waste heat. **Seasonal thermal energy storages (sTES)** are vital for peak-shaving, load-shifting, and increasing the usability of decentrally generated thermal energy. The INTERSTORES project is an initiative in energy innovation, focusing on the development of advanced seasonal thermal energy storage (sTES) systems. The project is funded through the Horizon 2020 Innovation Action (IA) Program and started in January 2024, concluding in December 2027. It contributes to **increasing the global market viability of sTES** systems by highlighting their advanced technological features, economic benefits, and positive environmental impacts. Aimed at optimizing the efficiency of thermal storage technologies, the project seeks to integrate these systems into current energy infrastructures, reduce production costs, and propel the technology to a level suitable for commercial use.

INTERSTORES is focused on re-using industrial infrastructure into renewable sTES systems (Reno-sTES) and using rock caverns for large-scale thermal energy storage (Giga-CTES). Within these two categories, the project supports the construction of two unique facilities: a **Reno-sTES in Ingolstadt**, Germany, and a **Giga-CTES Vantaa**, Finland. The Reno-sTES facility incampus will be established within an existing basin infrastructure, showcasing a strategic approach that reduces the initial investment needed for new developments by reusing industrial water reservoirs. Giga-CTES will be the first extra high temperature (above 100 °C) CTES system to be connected to a district heating network.

This recycling strategy aligns with the principles of the **circular economy, ensuring a limited ecological footprint and land utilization**. In contrast, the Giga-CTES site VECTES will utilize natural geological formations as storage sites. By excavating a cavern out of solid rock, this facility is designed to house approximately one million cubic meters of water, offering significant storage capabilities and high temperatures. This large-scale storage aims to benefit from economies of scale, making the initiative cost-effective and promising for future market expansion.

The planned full-scale demonstration of sTES technologies will **address critical gaps in reliable facilities, robust operational functioning, and replicable implementation**. The two solutions will provide insights into optimal design, integration potential on different scales, operating conditions, costs, and environmental impacts. The project will tackle the latter by holistic environmental evaluation through a life cycle assessment framework, as well as by local environmental impact assessment. A fundamental element of the project thus is the **development of tailored monitoring strategies focused on measuring local environmental effects and consequences**. This development is integrated into the sTES planning, installation, and operation phases of the sTES variants at both demonstration sites and is intended to serve as a blueprint for replication sites.



## 1.2 Goal and Scope

Environmental monitoring plays a crucial, multifaceted role in underground sTES (seasonal Thermal Energy Storage) projects. It is an indispensable tool, ensuring not only effective, but also efficient, safe, and sustainable long-term operations. Monitoring provides essential data on the environmental impacts of sTES operations, enabling stakeholders to make informed decisions regarding management and optimization. Therefore, it is vital to ensure **compliance with regulations, protect natural resources, and maintain public confidence**. Further, environmental monitoring acts as a safeguard against potential environmental and economic risks, ensuring that sTES do not compromise surrounding ecosystems.

As sTES technologies evolve and expand, the integration of advanced monitoring will become increasingly essential to long-term viability. The ability to continuously assess and adapt to environmental conditions will be one key factor in the sustainable development of sTES systems. Advanced monitoring techniques provide real-time data, allowing for the early detection of diverse issues, thus preventing long-term inefficiencies. Moreover, these techniques can offer deep **insights into interactions between the sTES systems and their surrounding environments**, leading to more refined and effective designs in the future. As the field progresses, the importance of sophisticated monitoring cannot be overstated.

The scope of this report focuses on **local, site-specific environmental effects** of sTES and their linkages to the overall technical, economic, and environmental performance. By examining these domains, it provides a detailed analysis of how localized environmental impacts can influence the broader success of sTES projects. This approach ensures that all aspects of system performance are considered, from the technical efficiency of heat storage and retrieval to the economic feasibility and environmental sustainability of the entire project. The report places special emphasis on the **experiences gathered during the first phase of the INTERSTORES project**, which involved detailed monitoring and analysis at two demonstration sites. These sites represent two distinct applications of sTES technology: Reno-sTES and Giga-CTES, both of which are designed for seasonal heat storage.

The **Reno-sTES** and **Giga-CTES** demo sites provide valuable case studies that illustrate the practical challenges and opportunities associated with the deployment of sTES systems. By focusing on these specific applications, the critical role of environmental monitoring in the early stages of sTES projects is highlighted. The data collected from these sites offers insights into the real-world performance of sTES systems, revealing how they interact with local environmental conditions and how these interactions can be managed to optimize system efficiency and sustainability. The **lessons learned from these initial phases** of INTERSTORES can guide future sTES developments, ensuring that systems can be scaled and applied widely with confidence in environmental and economic benefits.

In summary, the goals of this report are:

- Categorization of environmental monitoring procedures, technologies, and data types relevant to site-specific sTES characterization and its ambient domains;
- Identification of generally applicable and transferable monitoring concepts based on early experience at the INTERSTORES demo sites;
- Contrasting the environmental monitoring procedures and techniques for the two different subsurface heat storage applications, i.e., small-scale subsurface basins vs. large-scale underground caverns;
- Characterization of the relationship between tailored environmental measurement and sustainable management;
- Characterization of the relationship between transparent environmental measurement and public acceptance.

### 1.3 Structure of the Report

The report on monitoring concepts for sTES ambient domains is structured as follows:

The first chapter explains the **foundational aspects and perspectives of monitoring**, covering essential principles like the importance of data collection, the role of technology, and the challenges inherent in monitoring complex systems such as underground seasonal thermal energy storage. This discussion builds up the ground for understanding the broader context of environmental monitoring.

In the second chapter, this report offers **guidance on the phases involved in developing monitoring concepts**. Thereby, it details the processes of site assessment, preparation, installation, operation, and data use/reporting. Drawing from the INTERSTORES' practical examples, this section provides insights intended to help planners and engineers navigate these stages effectively, ensuring that the monitoring systems are robust and appropriate for their purpose.

Thirdly, a detailed examination of the **monitoring concepts of INTERSTORES** focuses on the two demonstration sites: incampus in Ingolstadt, Germany, and VECTES in Vantaa, Finland. Each site is briefly described, highlighting its unique geological and environmental conditions, to inform the design and implementation of the required monitoring systems. Then, existing environmental monitoring schemes at each location are outlined, including the specific methods and technologies employed to track key parameters. Additionally, the report discusses how these monitoring efforts have been expanded for research purposes within INTERSTORES, incorporating advanced sensors and new data analysis tools to enhance the monitoring capabilities. Where possible, the report presents preliminary data, offering early insights into the effectiveness of the monitoring concepts. These initial results help to illustrate how the concepts discussed earlier are being applied in practice and provide a foundation for ongoing refinement and optimization.

Finally, in the **conclusion** chapter, a short reflection emphasizes lessons learned and also looks ahead, considering potential future advancements and a broader application of these concepts. This forward-looking perspective underscores the importance of continuous innovation and collaboration in the field of environmental monitoring, ensuring that such systems remain effective and sustainable as the technology and its applications evolve.

## 2 Environmental Monitoring Concepts of sTES in General

### 2.1 External and Internal System Relevance

Environmental monitoring is crucial for the **safe and effective implementation of underground sTES**. This involves the continuous assessment of environmental parameters to ensure that sTES operations do not adversely impact the surrounding hydrosphere, ecosphere, human health, or the geological stability of the storage site (Bauer et al., 2017; Bott et al., 2019; Gonzalez-Ayala et al., 2024). Environmental monitoring thus is essential to ensure the system's effectiveness, long-term safety, and minimal environmental impact. The following section thus highlights the relevance of environmental monitoring, focusing on its key targets.

#### 2.1.1 External Effects on Environmental Receptors

##### Thermal pollution

Depending on the level of insulation, synthetic subsurface sTES basins (Tank Thermal Energy Storage, TTES; Pit Thermal Energy Storage, PTES; Water-Gravel Thermal Energy Storage, WGTES) or caverns (Cavern Thermal Energy Storage, CTES) release heat to the surrounding soil, rock, and (ground)water. This causes thermal changes in a typically relatively stable natural thermal regime of the ambient environment. In particular, significant **changes in groundwater temperature can impact its chemistry and biology**, affecting ecosystems and drinking water sources (Blum et al., 2021; Griebler et al., 2016; Noethen et al., 2023).

##### Contamination risks

sTES systems can potentially contaminate soil and groundwater with chemicals used in the systems (e.g., the release of corrosion compounds, ageing of insulation or basin structure) and conduits (e.g., heat carrier fluids). Monitoring for **pH, harmful elements, organic compounds/microbiological changes, and other pollutants** in such cases is vital. In this respect, monitoring groundwater quality helps detect and prevent contamination (Bayer & Finkel, 2006; Dahash et al., 2019).

##### Geological stability

Excavation, drilling, and induced temperature changes in the ambient ground can deteriorate geological stability and lead to ground subsidence or uplift (Vidal et al., 2022). For instance, thermal changes may in some specific geological environments cause an **expansion or contraction of subsurface materials** (De Simone et al., 2013) and closed fractures may open during ambient cooling of the (bed)rock mass that hosts a CTES.

Furthermore, drilling and excavation may create new pathways for fluid (e.g., groundwater) migration and change the hydraulic and hydrochemical conditions, which can – depending on the geological situation – be associated with **coupled geomechanical deformations** (e.g., gypsum swelling (Butscher et al., 2016)). Here, geomechanical monitoring helps in early detection and mitigation. Significant geomechanical deformations can induce microseismicity and felt seismicity (Dai et al., 2016; Jiang et al., 2023). Monitoring seismic activity ensures that any induced events are detected early and managed appropriately.

## 2.1.2 Internal Relevance for Sustainable Operation

### Optimizing system performance and energy efficiency

Monitoring allows for the optimization of (seasonal) thermal energy storage and retrieval processes, ensuring that energy losses are minimized and that the system operates at its peak efficiency (Bott et al., 2019; Nilsson & Rohdin, 2019; Nordbeck et al., 2020). Thereby, additional processing of **real-time data allows for operational adjustments** (e.g., supported by a digital twin) to improve efficiency and adapt to changing conditions.

### Achieving environmental/regulatory compliance and public trust

Regulatory frameworks often require stringent environmental monitoring to ensure compliance with environmental protection laws. Continuous monitoring and reporting help in adhering to these regulations (Liu et al., 2023). Besides that, transparent environmental monitoring practices help in **building public trust**. For example, by making monitoring data accessible to the public or other relevant stakeholders, sTES projects can **demonstrate their commitment to environmental stewardship** (Stemmler et al., 2024; Thomas et al., 2019).

## 2.2 Monitoring Life Cycle

### 2.2.1 Baseline Studies, and Preparatory Lab/Field Investigations

Before the initiation of sTES projects, preliminary investigations need to be conducted to understand any pre-existing environmental conditions (e.g., Dahash et al., 2019; Heldt et al., 2023; Pavlov & Olesen, 2012). These studies are used to provide a **reference point** against which changes can be measured during later operations. Thereby, the focus is set on preliminary measurements of groundwater flow regime and levels, the chemical composition of soil, rock, and groundwater; ambient soil and rock composition incl. thermo-physical properties, temperature trends, point measurements and profiles; ambient rock stress regime; existing flora, fauna and microbiology. Thus, these studies **should already cover all relevant domains** of/around a sTES (see Chapter 4.1.3).

### 2.2.2 Continuous Monitoring

This phase is essential to detect any **deviations from baseline conditions** that might indicate environmental impacts (e.g., Bolton et al., 2023; Lyden et al., 2022; Nußbicker-Lux et al., 2009). This includes in particular temperature monitoring to track changes in subsurface and groundwater temperatures, as well as water quality monitoring to detect any contamination or chemical changes in groundwater. Conversely, pressure monitoring to ensure that the storage processes do not create undue stress in geological formations, and geomechanical monitoring to observe any movements or deformations in the subsurface structures are to be considered during the operation phase.

### 2.2.3 Post-Operation Monitoring

To date, the end-of-life phase is rarely considered part of environmental monitoring, as the lifetime of sTES is generally considered unlimited (assuming correct maintenance) (e.g., Bott et al., 2019). In case of project closure, e.g., due to economic factors, public concerns, or technological failure, long-term post-operation monitoring may be necessary. It needs to **focus on critical features** among the features of continuous monitoring (e.g., subsidence, uplift, induced seismicity; long-term effects on groundwater flow/quality, ecology).

## 2.3 Domains

The interaction between sTES and the environment can be categorized into four different key domains to be considered for environmental monitoring concepts: Geosphere, Hydrosphere, Ecosphere, and Anthroposphere. By examining each domain more closely, this report aims to provide a comprehensive overview of **how sTES installations impact and are influenced** by geological structures, groundwater, ecosystems, and human health, thereby fostering sustainable integration of these technologies

### Geosphere

Most sTES, excluding some types like TTES, are often integrated at least partly into the subsurface, not only for aesthetic reasons but also for a more energy-efficient operation. For instance, **in Reno-sTES, the basins are embedded in Quaternary sediments** except for the top layer, which remains exposed. In contrast, the VECTES, as **Giga-CTES, is surrounded by crystalline, Pre-Cambrian bedrock**, resulting in full contact with their surrounding geosphere. Monitoring the interactions between sTES and the geosphere is therefore crucial to understanding and mitigating all potential impacts, such as subsurface temperature changes, geomechanical stresses, and alterations in the physical properties of soil and rock.

### Hydrosphere

The interaction of sTES with the hydrosphere primarily involves **groundwater systems**. Both sTES are in contact with meteoric (i.e., water affected by atmospheric circulation) groundwater and Giga-CTES can also involve a small amount of non-meteoric water. Baseline studies are necessary to establish and analyze the initial conditions of groundwater flow regimes, levels, and chemical compositions. Continuous monitoring helps detect any changes in groundwater temperatures, potential contamination, or chemical alterations that might result from the operation of the storage. Ensuring that the hydrological balance and water quality are maintained is essential for the sustainable deployment of sTES.

### Ecosphere

This domain encompasses **all relevant biological components** of the environment of a sTES system – for underground sTES focusing particularly on groundwater fauna. While the impact of ATEs and heat on groundwater fauna has already been studied (Brielmann et al., 2009, 2011; Griebler et al., 2016), there is little to no research on the impact of other sTES, especially its heat trace on surrounding groundwater fauna. Ongoing monitoring of this domain is however essential to validate the existing findings regarding sTES to other technology types. In this respect, baseline studies should include **assessments of existing biological communities** within the groundwater. Simultaneously, continuous monitoring would be able to track any ecological changes, ensuring that the impact on biodiversity is minimal and that ecological balance is maintained (Becher et al., 2022).

### Anthroposphere

The anthroposphere involves human activities and settlements that may be influenced by or have an influence on sTES projects (e.g., Blum et al., 2021; Bott et al., 2019). Baseline studies should assess the **socio-economic context**, including land use, population density, and local infrastructure. Monitoring this domain continuously afterwards helps identify any impacts on human health, property, and societal well-being, such as subsidence, issues in the quality of different water resources (incl. drinking water), or changes in local microclimates. For this domain, integrating any public concerns and feedback from communities around sTES systems is crucial to ensuring new projects are socially sustainable and accepted.

## 2.4 Technologies and Methods

Technologies and methods for environmental monitoring of sTES applications are manifold and can be distinguished concerning:

- spatial and temporal scale and resolution,
- accuracy and reliability,
- invasive and non-invasive,
- costs and impacts, their original discipline,
- as well as the domains they are focused on.

Spatial/temporal scale	One-time measurement	Seasonal measurement	Permanent datalogging
<b>A few centimetres to meters</b>	<div style="background-color: #4CAF50; color: white; padding: 5px; border-radius: 10px; text-align: center;">On-site Measurements</div> <div style="background-color: #9E9E9E; color: white; padding: 5px; border-radius: 10px; text-align: center; margin-top: 5px;">Borehole drilling, coring and logging</div>	<div style="background-color: #4CAF50; color: white; padding: 5px; border-radius: 10px; text-align: center;">On-site Measurements</div>	
<b>Close range around the storage</b>	<div style="background-color: #9E9E9E; color: white; padding: 5px; border-radius: 10px; text-align: center;">Geophysical investigation</div>	<div style="background-color: #4CAF50; color: white; padding: 5px; border-radius: 10px; text-align: center;">Laboratory (or on-site) testing of field samples</div> <div style="background-color: #4CAF50; color: white; padding: 5px; border-radius: 10px; text-align: center; margin-top: 5px;">On-site measurements</div>	<div style="background-color: #2196F3; color: white; padding: 5px; border-radius: 10px; text-align: center;">In-situ sensors and loggers</div>
<b>Further away from storage</b>	<div style="background-color: #FF9800; color: white; padding: 5px; border-radius: 10px; text-align: center;">Monitoring of stakeholders' disposition</div>	<div style="background-color: #4CAF50; color: white; padding: 5px; border-radius: 10px; text-align: center;">Laboratory (or on-site) testing of field samples</div> <div style="background-color: #4CAF50; color: white; padding: 5px; border-radius: 10px; text-align: center; margin-top: 5px;">Remote monitoring and sensing</div> <div style="background-color: #4CAF50; color: white; padding: 5px; border-radius: 10px; text-align: center; margin-top: 5px;">On-site Measurements</div>	<div style="background-color: #2196F3; color: white; padding: 5px; border-radius: 10px; text-align: center;">In-situ sensors and loggers</div>
Geosphere	Hydrosphere	Ecosphere	Anthroposphere

Figure 1: Summary of relevant monitoring methods concerning their temporal and spatial dimensions.

## 2.4.1 Borehole Drilling, Coring, and Logging

Borehole drilling, coring, and logging are essential in the investigation and characterization of subsurface conditions for various geotechnical and environmental projects, including sTES. They provide **in-situ data** on soil and rock properties. Through geophysical and geomechanical logging, borehole drilling offers insights into physical and mechanical characteristics, such as density, porosity, permeability, and strength. This is invaluable for understanding the behaviour of the subsurface under different conditions.

In addition to in-situ data collection, borehole drilling also yields **drill samples** that can be examined on-site or in a laboratory. These samples provide a direct, tangible record, allowing more comprehensive analyses of the properties of the materials. Laboratory tests on these samples may include assessments of grain size distribution, mineral composition, moisture content, and other parameters (see Chapter 2.4.3) that affect the performance of sTES.

Variants of borehole **drilling techniques** include direct push applications, which are particularly useful for shallow tests in unconsolidated ground. They involve driving a sampling device into the ground without the need for traditional drilling, which might be costlier, less efficient, or more disruptive.

## 2.4.2 In-Situ Sensors and Loggers

In-situ sensors and loggers are essential for **one-time, repeated, and real-time monitoring** of environmental parameters. Sensors deployed in wells, boreholes, and the surrounding environment provide local data or continuous data streams (Noethen et al., 2023). For thermal monitoring thermocouples and thermistors are placed in boreholes to measure temperature at various depths. For hydrogeological characterization, water level and pressure loggers are used. Aside from this, in-situ sensors in wells can continuously monitor water quality parameters (e.g., Einarson & Cherry, 2002; Venkatesh et al., 2024).

Further, Fiber Optic **Distributed Temperature Sensing (DTS)** can be employed, which uses optical fibres to provide continuous temperature profiles over long distances (Zhang et al., 2021). This technology provides high-resolution, real-time data on temperature variations, making it ideal for monitoring temperature changes in soil, water, or inside infrastructures. Its ability to cover large areas and operate in different domains is another advantage of this method.

Finally, **geomechanical in-situ monitoring** ensures that storage processes do not create undue stress in geological formations (Bock, 1994; Fernandes & Chaminé, 2023), e.g., pressure transducers installed in boreholes measure subsurface pressures; inclinometers record changes in the angle of subsurface structures; and extensometers can be used to monitor the displacement between two points in the subsurface.

## 2.4.3 Laboratory (or On-Site) Testing of Field Samples

### (Ground)water samples

Samples from groundwater play a critical role in the detailed **characterization of water quality**, providing data on a variety of parameters that, e.g., influence environmental health. Water samples can be analysed for a range of chemical, physical, and biological properties, including pH levels, concentrations of specific elements (e.g., harmful elements), the presence of organics, microbial content, and the diversity and abundance of groundwater fauna. In addition to chemical and biological analysis, groundwater samples can reveal important information about the geochemical **processes occurring within an aquifer**,

such as the dissolution or precipitation of minerals, redox conditions, and the potential for contamination transport. The presence of heavy metals, for instance, may indicate natural mineralization processes or contamination from other anthropogenic sources. **Microbial content analysis** in water samples can provide insights into the biological activity within the groundwater system, including the roles of microorganisms in biogeochemical cycles. Furthermore, the study of **groundwater fauna**, such as small invertebrates, can serve as bioindicators of water quality and ecosystem health, offering a broader perspective on the ecological impacts of subsurface activities (Becher et al. 2022).

### Rock and soil samples

Samples of **rocks and soil**, secondly, are fundamental to the geomechanical, hydraulic, and thermal characterization of subsurface environments.

In **geomechanical tests** (e.g., uniaxial compressive strength tests, triaxial tests, and shear tests), these samples are subjected to stresses to determine their strength and deformability. This is crucial for stability analysis, particularly in the context of underground construction of sTES, where understanding the mechanical behaviour of rock and soil is essential to prevent structural failures.

In **hydraulic tests**, rock and soil samples are used to estimate porosity and permeability, two key parameters that influence fluid flow in subsurface environments. Porosity refers to the volume of void spaces within a material, while permeability describes the ability of fluids to move through these spaces. Accurate estimates of porosity and permeability are vital for predicting the behaviour of groundwater flow (Stauffer et al., 2013). These properties are also important for understanding the potential for fluid migration in shallow geothermal systems (e.g., the geothermal trench in INTERSTORES).

**Thermal tests** on rock and soil samples are conducted to identify thermal conductivity and heat capacity. Both are critical for evaluating thermal performance: While thermal conductivity measures the ability of a material to conduct heat, heat capacity indicates how much heat energy a material can store. These properties are particularly important in the design and operation of all applications where heat transfer plays a role (Stauffer et al. 2013). By understanding the thermal properties of the subsurface, the efficiency of these systems can be optimized, ensuring that heat is stored and retrieved effectively and that thermal losses are minimized.

## 2.4.4 On-Site Measurements

A variety of probing options can be used to hydraulically and hydrochemically characterize groundwater via on-site measurements. In contrast to permanent logging, **manual measurements** can cover a broad area, providing a more general overview of surrounding conditions. Hydrogeological experiments, such as pumping tests, can be conducted to characterize an aquifer from different perspectives. They involve extracting water from a well at a constant rate and observing the change in hydraulic head in the pumping well and surrounding observation wells. Based on this, for example, hydraulic conductivity and transmissivity can be derived (Butler Jr., 1990; Leven & Dietrich, 2006; Lewin et al., 2014).

In addition to seismic, geophysical, and temperature sensors, fibre optic **distributed temperature sensing (DTS)** is particularly relevant. These tools provide real-time, high-resolution data on temperature variations throughout the storage medium, allowing for precise monitoring of heat distribution and retention over time (Selker et al., 2006; Silixa Ltd., 2022). By integrating thermal monitoring techniques with geophysical and seismic methods, it is possible to create a comprehensive picture of both thermal and mechanical behaviour.

## 2.4.5 Geophysical Investigation

Geophysical investigations offer **non-invasive, tomographic images** of subsurface structures (Everett, 2013). They can depict, for example, the layering of geological formations that are critical to operation. Techniques such as electrical resistivity tomography (ERT), ground-penetrating radar (GPR), and thermal imaging are particularly well-suited for assessing the integrity and performance of the subsurface (Bergmann et al., 2012; Coscia et al., 2011; Daniels, 2000; Utsi, 2017). These methods provide detailed insights into the distribution and movement of heat, helping to identify areas of potential heat loss or detect changes in moisture content (Cultrera et al., 2018; Hawkins et al., 2017; Yang et al., 2021).

Seismic monitoring, though more commonly associated with detecting tectonic activity or monitoring for induced seismicity, can be adapted for sTES to detect micro-seismic events that might indicate subsurface movements or changes in material properties due to thermal expansion and contraction. The use of **seismometers** in this context helps to monitor the mechanical response of the subsurface to repeated cycles of heating and cooling, which are inherent to sTES operation. Detecting even minor shifts or stress changes in the subsurface is crucial for assessing the structural integrity of storage and ensuring that the cyclic thermal changes do not lead to subsidence, fracturing, or deformations.

Moreover, long-term monitoring using geophysical techniques enables the detection of gradual changes in subsurface conditions. For instance, **shifts in groundwater flow patterns** could influence heat transfer efficiency or the emergence of thermal anomalies could signal localized material degradation.

## 2.4.6 Remote Monitoring and Sensing

Remote monitoring and sensing are advanced techniques that utilize **satellites and drones** to gather environmental data. These technologies are capable of tracking environmental parameter values over large areas and detecting changes that might indicate shifts in subsurface conditions. Devices equipped with thermal sensors can monitor surface temperature changes that are indicative of underground variations, e.g., heat distribution, thermal leakage, or changes in moisture (Jackson, 2002; Lakhankar et al., 2009; Qin et al., 2002).

Remote monitoring systems can be based on **multispectral or hyperspectral sensors**, providing information on vegetation health, land use, and surface water dynamics. These insights may reveal effects on local ecosystems and water resources. By integrating these data with ground-based measurements, a more complete picture of sTES can be built.

Generally, proper **telemetry technologies** need to ensure that data from in-situ sensors is efficiently transmitted to central databases for real-time analysis. These systems can work with a variety of sensors embedded in the subsurface or on-ground, e.g., temperature, moisture, or pressure sensors. Telemetry allows for continuous monitoring without a need for frequent visits, significantly reducing costs and enabling fast response to anomalies. Hence, this real-time data transmission is particularly useful for warning systems, where timely information is critical for mitigating potential environmental or operational issues.

An integration of remote monitoring with **data analytics and machine learning** can yield the ability to predict future trends. By combining historical and real-time data patterns and correlations might be identified, leading to more proactive and effective management.

## 2.5 Data Management & Analyses

Robust, well-structured, site-related data management systems are essential for collecting, processing, and analyzing the **vast amounts of data** generated by environmental monitoring procedures. Specifically, data management and analyses concern the following scope and goals:

- **Centralized** data management such as executed in INTERSTORES facilitates the normalization of raw data, secure storage and IPR management, and remote access for collaborative and interdisciplinary data exchange.
- Data **analytics** software is employed as a tool to analyse data trends, perform predictive analysis, and generate reports. For instance, Geographical Information Systems (GIS) integrate spatial and temporal data for comprehensive analysis and visualization. Moreover, machine learning algorithms are used to analyse large datasets, identify patterns, and predict potential environmental impacts.
- Data **processing units and models** (models for virtual site representation, digital twins, data-based statistics, machine learning tools, etc.) facilitate purpose-built interpretation and process-based analysis.
- **Real-time** feeding of the data management system and data processing units (e.g., digital twin) enables real-time alerts for immediate response, e.g., to potential environmental hazards. For instance, SCADA Systems (Supervisory Control and Data Acquisition) collect data from sensors and instruments for real-time monitoring and control. Moreover, the integration of IoT (Internet of Things) and remote sensing technologies allows for remote monitoring of sTES sites, enhancing the ability to manage and respond to environmental issues from a distance.
- **Long-term trend analysis** of data allows understanding of the impacts over time and adjusts operational strategies.

## 2.6 Application of Data for Modeling and Simulation

Collecting data for modelling and simulation of sTES, the surrounding energy system, and the ambient, is crucial for setting up a **digital twin**, ensuring model accuracy and reliability, as well as optimizing design and operational efficiency. The following categories of criteria relevant to the application of collected data for modelling and simulation can be defined:

### Accuracy

Model accuracy and calibration are critical components in the development and validation of simulation models, including digital twins. Real-world data derived from laboratory experiments and field investigations serve as **empirical evidence** that not only validates but also calibrates these models. Without such data, models rely heavily on assumptions and theoretical values that may not accurately reflect the complexities of real-world conditions. The accuracy of these models hinges on the **precise determination of key parameters**, including thermal conductivity, heat capacity, soil and groundwater properties, and variations in ambient temperature. They are most reliably obtained through direct measurements, ensuring that the models are grounded in reality.

### Process Identification

Data collection plays a crucial role in understanding **intricate environmental interactions** at play, particularly in how heat is transferred and stored within a sTES. These processes,

which encompass, among others, conduction, convection, and radiation, are influenced by material properties and environmental conditions. Furthermore, the interaction between storage and local elements, such as groundwater, precipitation, and evaporation rates must be meticulously modelled to accurately predict water levels and potential heat loss. There, field data offers insights into these interactions, allowing for a more comprehensive understanding of the system's behaviour under varying conditions.

### Design Optimization

Accurate data is pivotal in the optimization of the design of sTES. For example, determining appropriate **sizes and configurations** of systems is essential, as over- or under-sizing can lead to inefficiencies and increased costs. Different **materials** possess varying thermal properties, and laboratory tests are used to identify the most suitable construction materials. These materials not only optimize thermal storage but also minimize losses, contributing to a more efficient and cost-effective system.

### Operation Surveillance

Operational efficiency is another area where data collection is critical. By monitoring the sTES' performance over time, operators can generate a versatile, site-specific, and reliable digital twin. This digital twin serves as a dynamic model that reflects the real-time performance of the basin, allowing for the **identification of any deviations** from the intended operational behaviour. Once detected, corrective measures can be implemented promptly, ensuring efficient operation. Continuous monitoring of energy inputs and outputs, e.g., heat and cold balances, further enhances the system's operational efficiency, enabling it to meet the demands placed upon it with precision.

### Climate Adaptation

Sensing and monitoring data related to seasonal temperature variations, solar radiation, and other climatic factors are essential for accurately modelling how an sTES will perform. This data allows for designing systems that can effectively store and release thermal energy as needed, **accommodating seasonal demands**. Moreover, by understanding long-term climatic trends through the analysis of historical data, sTES can be designed to be more robust, withstanding future changes in climate patterns and ensuring long-term viability.

### Economic Perspective

Cost data can allow for in-depth cost-benefit analyses, considering initial construction costs, ongoing operational costs, and savings from reduced energy consumption. Efficient **resource management**, made possible by accurate data, leads to reduced waste and lower operational costs, thereby enhancing the overall economic feasibility of the system.

### Legal Perspective

Regulatory compliance and safety are critical considerations for constructing and operating sTES. Transparent field data is essential for assessing environmental impacts, and ensuring that they **comply with regulations**. Information on soil stability, groundwater levels, and other local conditions is crucial for assessing risks associated with both the construction and ongoing operation of the basin, safeguarding both the environment and public safety.

### Technology Advancements

Data collection is a driving force behind **innovation and improvement**. By gathering data from a variety of sources, benchmarks identify best practices and foster innovation. Detailed, continuous data collection supports research and development efforts, leading to continuous improvements in technology and methodologies. This evolution ensures that these systems remain at the cutting edge of efficiency, reliability, and sustainability.

### 3 Development of Monitoring Concepts

The development of a monitoring concept is a methodical and **iterative process**. It covers a framework to collect, analyse, and utilize data effectively. Thereby, conceptualization, planning, and implementation, as well as the use of data in environmental monitoring are separate components.

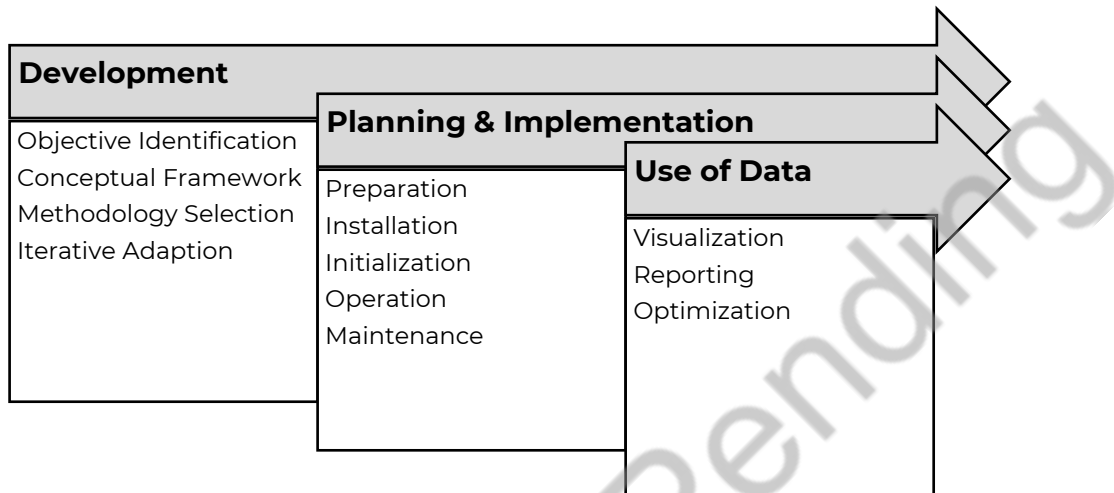


Figure 2: Recommended aspects and stages of the development of a monitoring concept within the setting of INTERSTORES and for related projects.

This chapter provides an example of how these processes can be **tailored to specific challenges and characteristics**, ensuring safe and efficient operation while minimizing environmental impacts.

#### 3.1 Concept Development

##### 3.1.1 Objective Identification

The process is initiated with the identification of objectives, which are shaped by the specific goals of a related project, stakeholder expectations, and regulatory requirements. These objectives must be **clearly defined** to determine what needs to be monitored, why it is important, and how the data will be used to enable informed decisions.

In sTES projects, this must account for the unique challenges posed by subsurface thermal storage systems over their entire monitoring life cycle (see Chapter 2.2). Thereby, the primary objective of any monitoring concept for a sTES project is to ensure the **safe and efficient operation** of the storage system and minimize environmental impacts.

##### 3.1.2 Conceptual Framework

In the second stage, a conceptual framework outlines the **scope of monitoring activities**, including environmental, technical, and operational parameters (see Chapter 2.4). It further defines methods for data collection, frequencies, and technologies to be employed. It must be comprehensive enough to address all potential risks and impacts while being flexible enough to accommodate changes as the project evolves.

A framework within sTES projects needs to monitor a range of parameters related to the thermal, mechanical, and chemical processes within a STES and its environment. As part of sTES projects, the concepts need to **address the interaction** between the sTES and the geosphere, hydrosphere, ecosphere, and anthroposphere (see Chapter 2.3).

### 3.1.3 Methodology Selection

A specific selection of methods, technologies, and data management systems involves a careful evaluation of available options to identify **appropriate tools and techniques** (see Chapter 3.1). Considerations should include the accuracy and reliability of sensors, the feasibility of deploying selected technologies in the field, the ability to harmonize data from multiple sources, and associated costs. Also, a selection of data storage and analysis systems is crucial, as they might be handling large volumes of data, providing real-time analysis, and ensuring data security and integrity.

The selection of monitoring methods and technologies for sTES projects must consider the **specific conditions of the subsurface environment**. For example, sensors used to monitor temperature and pressure in the subsurface must be capable of withstanding high temperatures over long periods. The choice of data storage and analysis systems (see Chapter 2.5) should involve alerts in case of any deviations from expected conditions.

### 3.1.4 Spatial Selections

For the selection of monitoring locations, the **placement of sensors and other equipment** must be strategically planned to ensure that the data collected is representative of the entire system and its interactions with the surrounding environment. This may involve identifying **key areas** where environmental impacts are most likely to occur, as well as ensuring that monitoring covers all relevant aspects of the system's operation.

The selection of locations in sTES projects is guided by the need to obtain a comprehensive understanding of the interactions between the storage and the environmental domains (see Chapter 2.1). Key locations are areas of highest projected impacts, i.e., where thermal or pressure gradients are expected to be highest, or where groundwater flow is most likely to be affected. Also, the placement must consider potential future changes in the system, e.g., the introduction of new technologies.

### 3.1.5 Iterative Adaption

A refinement through **consultations with both internal and external stakeholders** may involve project developers, regulators, environmental scientists, and other relevant parties (see Chapter 3.2). They should be requested to provide feedback to ensure the monitoring program is feasible, relevant, and aligned with the multifaceted goals of the overall related project. Multiple rounds of feedback and adjustments are required to refine the objectives, modify the scope, or select alternative methods.

Within sTES projects, technical experts and project developers may provide input on the **feasibility of methods in practice**, and the integration of these activities with the other operational aspects of the overall system.

## 3.2 Planning & Implementation

The planning and implementation stages **translate the conceptual framework into actionable steps**, from an initial site assessment to ongoing operation and maintenance of the monitoring system. This requires careful coordination, attention to detail, and the ability to adapt to changing conditions or unforeseen challenges.



Figure 3: Individual phases of planning and implementation of a monitoring concept.

Planning and implementation are critical due to the **complex and long-term nature of subsurface processes**. Thus, site assessments involve detailed geological and hydrological studies to understand subsurface conditions and to identify specific challenges. They provide the baseline data necessary for designing a monitoring system that can detect changes in temperature, pressure, and other critical parameters over time.

### 3.2.1 Preparation Phase

This phase begins with a comprehensive site assessment, including preliminary studies such as literature reviews, **analysis of existing information**, and the creation of detailed site maps. These studies provide the necessary background information to understand the **baseline conditions**. A site assessment must involve information on the local environment, including geological, hydrological, ecological, and socio-economic factors (see Chapter 2.3). This information is crucial for defining the specific monitoring requirements and for ensuring that the monitoring system is designed to capture all relevant data.

Based on this, a **detailed monitoring scheme** is developed. This scheme includes the selection of sensor types and the determination of optimal locations for sensor placement. The scheme also outlines the data collection procedures, calibration protocols, and standards for data storage and analysis. The preparation phase also includes **logistical considerations**, e.g., the procurement of equipment, hiring of personnel, and coordination with contractors or other stakeholders involved in the installation process.

The preparation phase within sTES projects involves the selection of sensors that are capable of withstanding harsh conditions of the subsurface environment. The monitoring scheme must also account for the **spatial variability of subsurface conditions**, ensuring that sensors are placed in locations where they can capture the most relevant data. For example, sensors may be placed at different depths within the sTES to monitor gradients, or at key locations within the surrounding domains.

### 3.2.2 Installation Phase

The installation phase involves the **physical deployment of monitoring equipment** at the selected locations. This step requires careful coordination to ensure that the equipment is installed correctly and that it is positioned in locations that will provide the most accurate and reliable data. The installation process may involve drilling, trenching, or other forms of excavation (see Chapter 2.4.1), depending on the specific requirements of the monitoring system and the characteristics of the site. In addition, this phase involves the setup of data telemetry systems (see Chapter 2.4.6), power supplies, and all other **infrastructure** necessary for the operation of the monitoring system.

Within sTES projects, the installation phase may involve drilling deep boreholes, installing sensors in confined spaces, or deploying equipment in **remote or difficult-to-access locations**. The process must be carefully planned and executed to ensure that the sensors are securely anchored. This also involves data transmission systems that can operate reliably in challenging conditions of a subsurface environment.

### 3.2.3 Initialization Phase

After installation, calibration ensures that sensors are accurately measuring the intended parameters and that the data collected is reliable. This process may involve comparing the readings with standards, adjusting the sensor settings to correct for any discrepancies, and conducting test runs to **validate the system's operation**. Initialization involves setting up data collection schedules, configuring the data storage and analysis systems, and introducing plausibility checks.

In sTES projects, this phase may involve the **use of reference measurements** taken during the site assessment phase or specialized calibration equipment designed for high-temperature or high-pressure environments. The initialization involves configuring analysis systems to account for specific conditions, such as the expected temperature ranges or the time scales over which changes are likely to occur.

### 3.2.4 Operation Phase

The operation phase involves **continuous collection, analysis, and interpretation** of data. Automated schedules can ensure that data is collected at regular intervals and that data from different sensors is harmonized to provide a comprehensive overview. **Visualization** tools can present the information clearly and accessible, allowing for the identification of trends, anomalies, or potential issues. All data must be stored securely, with regular backups to prevent data loss (Butean et al., 2024).

Monitoring systems of sTES continuously collect data on predefined key parameters. This data is analysed in real-time to detect any deviations from expected conditions, allowing for early intervention if necessary. Also, long-term performances of the systems can be tracked, providing insights into efficiency and sustainability. Visualization tools such as **temperature distribution maps or pressure trend graphs** are recommended to enable informed decisions.

### 3.2.5 Maintenance Phase

Maintenance is an ongoing requirement to **ensure the continued operation** of the monitoring system. This involves regular manual checks of the sensors and other equipment, as well as **periodic recalibration** to account for any changes in all domains. Maintenance also includes the replacement components as they reach the end of their operational life or as new technologies become available. Adaption to new conditions, such as changes in the project scope or environmental factors, is also an essential part. Hence, maintenance is essential to ensure the long-term viability of the monitoring system and to prevent any disruptions to the data collection process.

### 3.3 Use of Data

The use of data in environmental monitoring is a multifaceted process involving **analysis, interpretation, and dissemination**. The ultimate goal is to provide actionable insights that inform decision-making, ensure compliance with regulatory requirements, and contribute to the optimization of the system being monitored. All monitoring activities must be processed and analysed in a way that makes them meaningful and accessible, allowing them to identify trends, assess risks, and take corrective actions as necessary.

The use of data is critical to ensuring the safe and efficient operation of sTES systems. The data collected through monitoring activities is used to track the performance of the system, **identify potential issues, and optimize the storage**. At the same time, the monitoring data is also used to assess environmental impacts and to ensure compliance with regulations.

#### 3.3.1 Visualization

Visualization makes complex information easier to understand: Tools such as **graphs, charts, and maps** can be used to illustrate trends, highlight key findings, and communicate the results of different domains (see Chapter 2.3) concisely. These visualizations can be included in reports (see below), presentations, or online dashboards, making the information available to a wide range of stakeholders in a format that is easy to interpret.

Visualization tools play a key role in the reporting process of sTES projects. For example, temperature distribution maps can be used to **illustrate the thermal performance** of the sTES, while, e.g., pressure trend graphs can highlight changes in the subsurface over time.

#### 3.3.2 Reporting

This aspect involves the **communication of results** to, among others, project managers, regulators, and the public. The format and content of reports can vary depending on the audience and the specific requirements of the project. **Regular reports** typically include an overview of the monitoring activities, a summary of the data collected, and an interpretation analysis of the results. They may include recommendations for further action or adjustments based on the findings. In addition to regular reports, **special reports** may be required in response to specific events. In sTES projects, this may be the detection of a leak or a significant change in subsurface conditions.

#### 3.3.3 Optimization

Optimization means using the data to improve the performance of the considered system. This may involve **adjusting operational parameters, implementing new technologies, or making changes to the design or configuration** of the system. This is an ongoing process that requires continuous analysis. Thereby, merged information of different key parameters is used to identify areas for improvement and to assess the impact of any changes made to the system.

In sTES projects, optimization involves adjusting, e.g., the **inlet temperatures or volumetric flow rates** within the storage or the energy system, implementing new technologies to enhance storage efficiency, or making changes to the design or configuration of the system.

## 4 Monitoring in INTERSTORES

### 4.1 incampus, Ingolstadt, Germany

#### 4.1.1 Site Description

The incampus site is located in the eastern part of Ingolstadt on the **former site of a refinery owned by BayernOil**, directly south of the Danube. The campus site is adjacent to the FC Ingolstadt stadium (Audi-Sportpark) in the south. To the west of the redeveloped area passes the A9 highway in a north-south direction (Dr. W. Knorr, 2018). Before being partitioned, the entire property covered an area of ca. 110 ha. With ca. 75 ha, the area to be converted thus covers more than 70 % of the former grounds of the refinery. The site is situated in a commercial district and is being **redeveloped into a research and development hub**. The incampus is set to feature up to 70 non-residential buildings, including offices, workshops, industrial laboratories, test benches, and computer centres.

The transformation of the incampus exemplifies contemporary land reclamation and redevelopment processes. Brownfields and existing structures are being repurposed through a collaborative effort involving public and industrial stakeholders. The development is organized into **four construction phases**. The first phase is underway, with initial buildings nearing completion and expected to accommodate approximately 1,400 workers (Faigl & Göttl, 2019). This expansion aims to establish a high-tech environment conducive to innovation, particularly in the automotive sector.

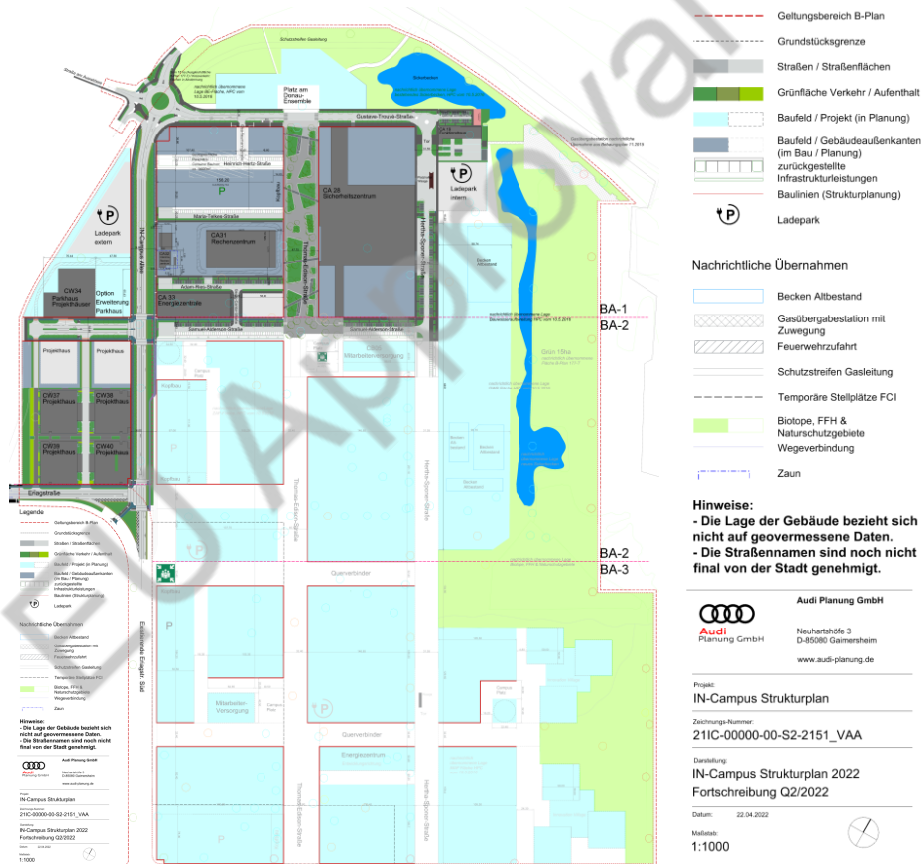


Figure 4: Overview of the incampus demonstration site (Audi Planung GmbH, 2022).

## Regional Geological and Hydrogeological Frame

The incampus site is geologically strongly influenced by the River Danube and predominantly contains sand and gravel, with post-glacial terraces. **Quaternary sediments**, mainly gravel with sandy and silty layers, are found 6-7 to 12 m below the surface and have high to very high permeability. Beneath this, the **Tertiary freshwater molasse** contains fine sands, silts, and clays with lower permeability, serving as limited groundwater aquifers (i.e., low permeabilities), but not as aquitards.

The site is located on a **floodplain once traversed by the River Danube**. A drainage ditch runs through the northwest, adjacent to the lake Auwaldsee, while the southern and south-eastern areas feature several oxbow lakes and gravel ponds. Thus, the site is surrounded by various **surface waters** (e.g., ponds, lakes, and trenches). The strata of the subsurface further ensure **stable groundwater conditions**. Groundwater, influenced by infiltration from the River Danube in the northwest, flows southeast at a rate of nearly 7,000 m<sup>3</sup> per day (Hilgert, 2014).

## Current Land Use in the Surrounding Area

The incampus is surrounded by areas that serve as nature and environmental protection zones. Although there are **no water protection areas designated near** the site (the next drinking water protection area is located 3.5 km to the south), there are still biotopes, areas subject to the Habitats Directive (*Fauna-Flora-Habitat-Richtlinie*), landscape conservation areas (*Landschaftsschutzgebiete*), nature conservation areas (*Naturschutzgebiete*), and bird sanctuaries (*Vogelschutzgebiete*) (Dr. W. Knorr, 2018). Further, **15 ha of the incampus site itself is being restored** to its natural state (Faigl & Göttl, 2019).

### 4.1.2 Synergies with Transformation/Remediation Activities

Due to >45 years of refinery operations, the site was contaminated with hydrocarbons (i.e., oil pollutants) in the soil and groundwater. Additional contamination was caused by fire-extinguishing foam. The conversion of the refinery site into a modern research and development park has been **one of the largest redevelopment projects** in Germany. It was considered the first full redevelopment of a refinery in Bavaria (Faigl & Göttl, 2019).

## Soil Treatment

During a **land levelling** process, around 65,000 m<sup>2</sup> have already been restored to a uniform terrain level by cleaning up the resulting “crater landscape”. This involved moving ca. 21,000 m<sup>3</sup> of soil (Faigl & Göttl, 2019). Over five years, the renaturation activities have **removed** ca. 900 tons of heavy fuel oil, ca. 200 tons of volatile contaminants, and ca. 100 kilograms of perfluorinated chemicals (Faigl & Göttl, 2019). The measures here included **excavation** up to 4 meters below groundwater level utilizing wet and dry dredging and excavation of deep sections utilizing overlapping drilled pits or honeycomb excavation (Hilgert, 2014).

It is important to note that the excavated material is partly available as **filling material for the Water-Gravel Thermal Energy Storage** facilities planned in INTERSTORES. A total volume of 5,200m<sup>3</sup> of available gravel is being considered for installation in all basins (Planungsgruppe M+M AG, 2023). These gravels are sampled in INTERSTORES as part of environmental monitoring and analysed concerning thermal and hydrogeological parameters.

## Groundwater Treatment

Contaminated groundwater is purified by employing a **drainage, purification, and re-infiltration (pump & treat)** system. Water from a downstream protection system is treated and returned to the aquifer through infiltration trenches and basins to prevent

contaminated groundwater from leaving the area. Specifically, water from local wells is directed into an infiltration basin on the north-eastern edge and a trench running northward. Pollution detected entering from the southwest led to the installation of an upstream protection system, which also treats and reinfiltrates groundwater on-site, similar to the downstream system (Poser, 2020). These measures are implemented continuously.

All **extraction and injection wells** are drilled to a depth of 10.0 to 14.3 m. The diameter is consistently 175 mm, and the filter length is fixed at 3 m. The average flow rates are between a minimum of 12-22 m<sup>3</sup>/h and a maximum of 13-25 m<sup>3</sup>/h (Poser, 2020).

### Thermal Exploitation of Groundwater and Surface Water

The water pumped through the groundwater purification plant can be passed through a **heat exchanger before re-infiltration** if there is a heat deficit or surplus thermal energy in the energy system of the incampus (Poser, 2020). This is a synergistic benefit, since for both measures, continuous temperature data of the water is recorded during the operation. In addition, for the thermal exploitation of river water, a connection to the River Danube is planned. This system will be implemented in the course of further expansion (Planungsgruppe M+M AG, 2021a). This data is available for the INTERSTORES environmental monitoring concept at the incampus.

### Implications

Due to remediation activities, it is likely that **changes in (hydro-)geological properties**, such as conductivity, have occurred. During the remediation process, soil replacement was conducted in certain areas. Additionally, in the air sparging fields, compressed air was or is being injected into the subsoil to remove volatile contaminants (Poser, 2020). Although it is expected that these interventions will not significantly alter hydraulic permeability beyond the natural range, the possibility of localized variations cannot be entirely dismissed and needs to be reviewed within the activities of the INTERSTORES project.

## 4.1.3 Existing Monitoring Concept and (External) Data

### Climate and Weather Data

The German Weather Service (DWD) has established **test reference year (TRY) datasets**. These are processed weather data records used particularly for thermal building simulation and the design of HVAC systems (Deutscher Wetterdienst, 2017). The data comprises selected meteorological parameters for different regions in Germany and can be downloaded free of charge (Deutscher Wetterdienst, 2024). The following information for each hour of the year is provided: (i) air temperature, (ii) atmospheric pressure, (iii) wind direction, (iv) wind speed, (v) cloud coverage, (vi) Water vapor content (vii) Relative humidity (viii) Direct solar irradiance (ix) Diffuse solar irradiance (x) atmospheric thermal radiation (xi) radiation from the earth's surface, (xii) quality bit (Deutscher Wetterdienst, 2017). These **standardized datasets** offer added value for modelling and simulation in INTERSTORES, as they ensure transferability to other locations and can also be used to represent the incampus location. For this reason, they are integrated into the INTERSTORES monitoring system as reference datasets.

**Weather station of Ingolstadt.** Real-time weather data from a nearby (ca. 6 km distant) weather station of the Ingolstadt-Manching airfield (DWD weather station no. 2410) are integrated with the project on demand. The weather station is located at an altitude of 364.0 meters. The measured values include the parameters of (i) air temperature (min, max, average), (ii) precipitation, (iii) humidity, (iv) wind speed, (v) wind direction, (vi) sunshine hours, and (vii) snow height. detailed information regarding the sensors as well as data can be downloaded via e.g., the DWD climate data centre (Deutscher Wetterdienst, 2024).



## Borehole Logs

**Public drilling database.** Due to the numerous groundwater monitoring wells installed at the incampus, detailed, site-specific information on the subsurface structure is known. This information is available via drilling documentation from subcontractors and data from the Bavarian State Office for Environment (LfU Bayern). The latter is recorded state-wide and available online free of charge via the "UmweltAtlas Bayern" (Bayerisches Landesamt für Umwelt, 2024b).

**Logs from previous activities.** Further data collected on a site-specific basis in connection with the remediation activities at the incampus can be found, for example, in drilling documentation (and expansion documentation) for the construction of groundwater measuring points in March 2022 (BauGrund Süd Gesellschaft für Geothermie mbH, 2022). Eight groundwater measuring points were installed across the entire construction area and documented following DIN 4022 (DIN 4022-1:1987-09, 1987). The information includes details on the drilling method, the dimensions, and - particularly relevant - the groundwater and the strata record of retrieved drill cores. As a result, the thickness and properties of subsurface formations are recorded.

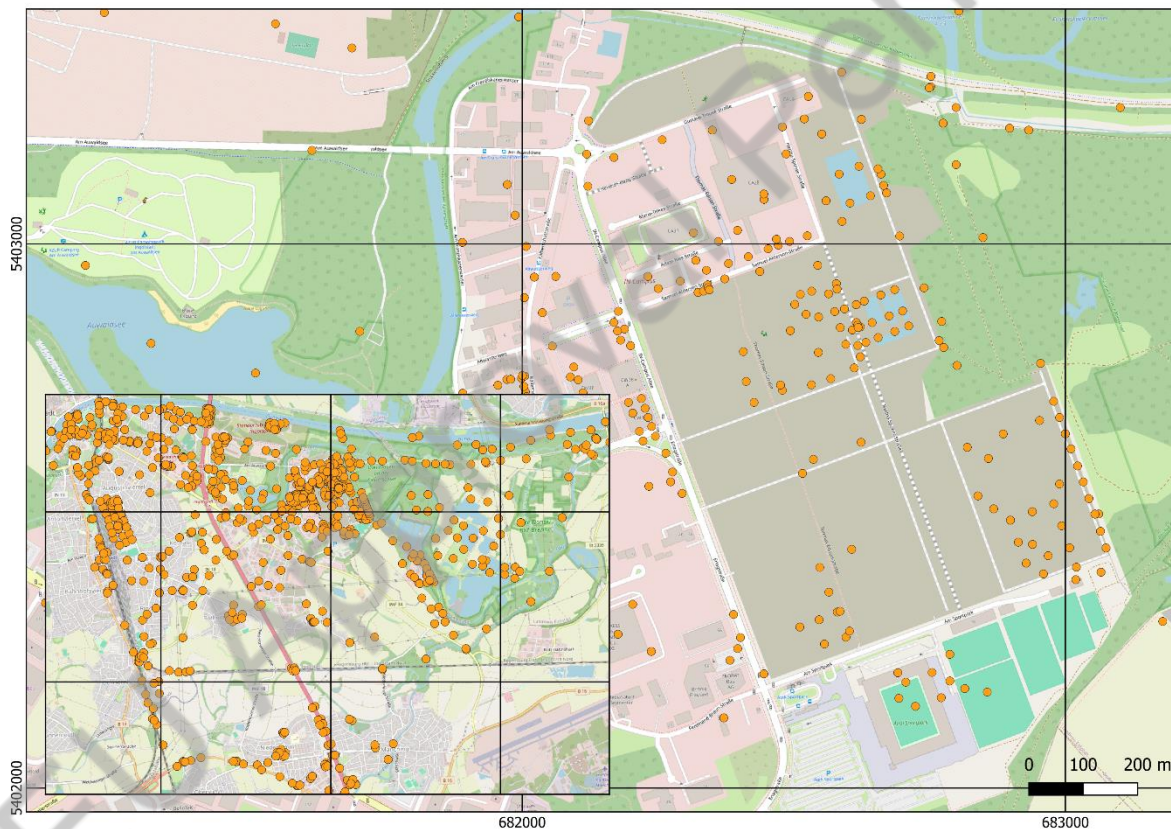


Figure 5: Overview of existing drilling information locations (orange dots) on the incampus site and in the vicinity of the demonstration site (Bayerisches Landesamt für Umwelt, 2024b; OpenStreetMap Foundation, 2024).

Both publicly available subsurface strata inventories and additional local documentation are available to INTERSTORES and are included in the monitoring database as static background information for the demonstration site.

### Thematic Base Maps

**Geological Map of Bavaria 1:25,000 (GK25).** The most detailed map series from the Geological Survey of Bavaria at the Bavarian State Office for Environment (LfU Bayern) shows unconsolidated and consolidated rocks at the ground surface, offering insights into the geological structure. The data package includes the digital Geological Map of Bavaria (1:25,000 scale), with metadata and visualization files. The map is based on various data sources and follows a standardized legend across Bavaria. It features geological units at depths greater than 0.7 meters, and structural lines like folds and faults (Bayerisches Landesamt für Umwelt, 2023).

**Hydrogeological Map of Bavaria 1:50,000 (HK50).** The hydrogeological map at a 1:50,000 scale (HK50) is developed as part of the Bavarian State Office for Environment's (LfU Bayern) hydrogeological state survey (Bayerisches Landesamt für Umwelt, 2024b, 2024a). This map details the distribution of hydrogeological units and surface cover layers, classified by aquifer type and groundwater permeability. It also provides information on groundwater levels in the main aquifers and the protective function of groundwater cover. The map includes surface data such as the distribution of cover layers, artesian groundwater areas, and groundwater levels. Additionally, it shows groundwater equations and point data including wells, exploratory boreholes, springs, sinkholes, discharge measuring points, and weather stations (Bayerisches Landesamt für Umwelt, 2024b, 2024a).

**Digital elevation model 1m (DEM-1).** The DEM of LfU Bayern represents the terrain surface without vegetation and buildings as a point cloud. This data was gained via airborne laser scanning and updated by reflighting. The most accurate DEM-1 (grid width 1 m) can be used for modeling and simulation within INTERSTORES and is obtained via the Bavarian State Office for Digitization, Broadband, and Surveying (Landesamt für Digitalisierung, Breitband und Vermessung, 2024).

### Hydrogeological Base Model

A **steady-state and a transient model** is available for the incampus. A calibrated hydraulic model was developed by ARCADIS Deutschland GmbH (ARCADIS Deutschland GmbH, 2010) for planning the remediation activities. The model was last updated in 2020 by R&H (Poser, 2020). Thereby, the model was converted from the original hydrogeological flow model to a transport model. Depending on the version, the model represents six (ARCADIS Deutschland GmbH, 2010) or two (Poser, 2020) subsurface layers. Preliminary investigations showed good agreement with measured values from a validation (Poser, 2020): The average deviation between calculated and measured values is within the measurement tolerance, i.e., less than 3 cm.

While the existing base model is available to the project, it contains boundary conditions and assumptions that **need to be reviewed and comprehensively adapted** as part of the INTERSTORES investigations. This applies in particular to groundwater extraction and re-infiltrations. Furthermore, the **integration of thermal processes** is to be implemented in INTERSTORES for the first time.

### Surface Water – Levels

The **River Danube**, situated in the north of the demo site, is monitored in Ingolstadt at a municipal water level meter. This station, identified by the number 10046105, is equipped with remote data transmission capabilities, allowing real-time monitoring and reporting of the river's conditions (here: water level, discharge). The station monitors a catchment area encompassing ca. 20,300 km<sup>2</sup>, providing data for, e.g., management of water resources, or flood prevention. Located at river kilometer 2,457.85, the station is located at 360.30 m elevation (Hochwassernachrichtendienst Bayern, 2024a).



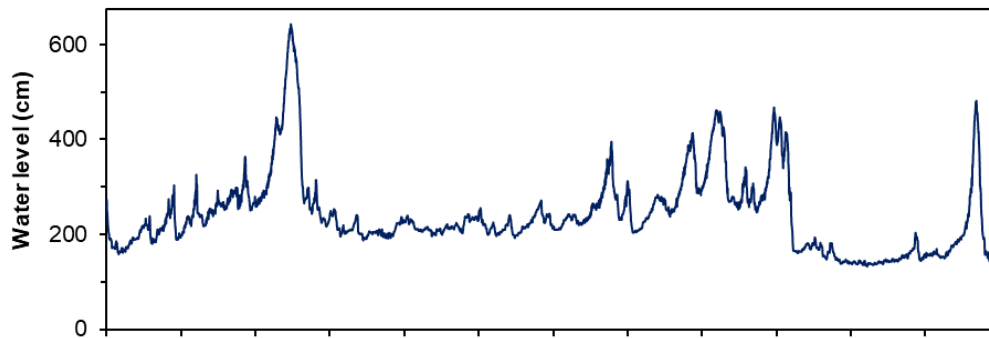


Figure 6: Hydrograph of the water level of the River Danube at the Ingolstadt gauge station, exemplified for the period August 2023 to August 2024 (Hochwassernachrichtendienst Bayern, 2024a).

Another municipal gauge with station number 13241005 (“Niederstimm”) is located in the **River Sandrach** in the south. The gauge of this smaller water body covers a catchment area of approx. 350 km<sup>2</sup> and is located at river kilometer 2.06 at an elevation of 350.94 m. As for the Danube, continuous measured values are also available for this gauge at 15-minute intervals (Hochwassernachrichtendienst Bayern, 2024b).

Specific **spot measurement campaigns** for surface water levels are available for October 2019. There, a monitoring campaign was carried out to characterize the site, involving the sampling of various open water bodies (Poser, 2020). The documentation includes a total of 36 monitoring points with accurate positioning. These level data (partly with limited vertical accuracy) are integrated into the INTERSTORES monitoring system.

### Surface Water – Temperatures

For the **Danube River**, the municipal water gauge (cf. “Surface Water – Levels”) provides temperature data, which is integrated into the monitoring of the site for this large adjacent surface water body. A data series since 01.11.1980 is available and is integrated into INTERSTORES’ monitoring system. Also, information on suspended particles and chemical parameters can be consulted if required (Hochwassernachrichtendienst Bayern, 2024a).

Furthermore, the surface waters of the **infiltration systems** at the site (see section “Surface Water - Pumped/infiltrated Quantities of the Water Treatment Plant”) provide additional monitoring stations where temperatures of these hydrogeologically relevant structures are recorded. More precisely, since 01.04.2022, temperature monitoring has been implemented at five locations within an infiltration trench (at different distances from the discharge systems) and at a reference water body to the east in a nature protection area (position determined in consultation with biological experts). The data is recorded every 6 hours and the monitoring is scheduled to run for three years until March 31, 2025 (Dr. B. Knorr, 2024).

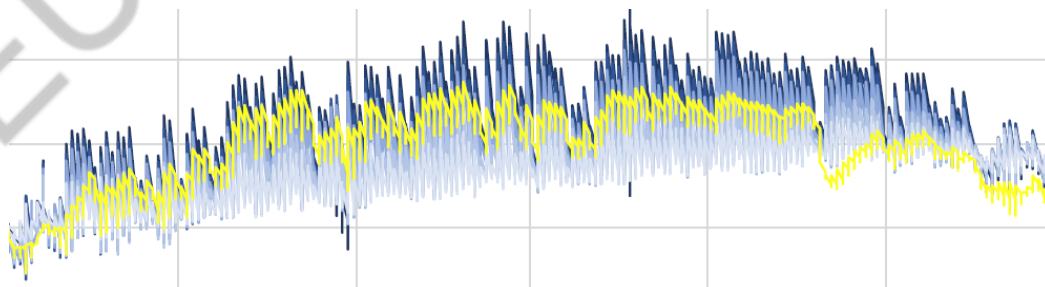


Figure 7: Data sets on surface water temperatures within and around the incampus (Dr. B. Knorr, 2024). For data privacy reasons, axis labelling has been excluded.

Specific **spot measurements** for surface water temperatures are available for October 2019. There, a monitoring campaign was carried out to characterize the site, involving the sampling of various open water bodies (Poser, 2020). The documentation includes a total of 36 monitoring points with accurate positioning. These temperature data (besides values of pH, conductivity, and oxygen content) are integrated into INTERSTORES' monitoring data.

### Groundwater – Pumping Tests

To confirm hydraulic characteristics and to **estimate the yield of the aquifer** as part of the remediation activities, multi-stage performance (pumping) tests of wells were carried out in the north of the site in May 2017 (Dr. W. Knorr, 2018). Gradients of the groundwater drawdowns were recorded and **hydrogeological parameters**, such as hydraulic permeabilities, transmissivities, and subsequent interpretations were derived. The results of the tests are available and will be used to further characterize the subsurface.

### Groundwater – Observation Points

Due to the long history of the operation of the refinery, the intense subsequent remediation efforts, and the use of the underground for the energy supply of the incampus, a large number of different groundwater observation points (**monitoring and/or extraction wells**) have been established. Some of these locations at the incampus have already been deconstructed, as they were only used for specific activities. In any case, this provides an **outstanding pool of data** that delivers high-resolution information about the incampus over a long period. Various **historical and current data** are available and are structured, integrated, interpreted, and used further as part of the monitoring in INTERSTORES.

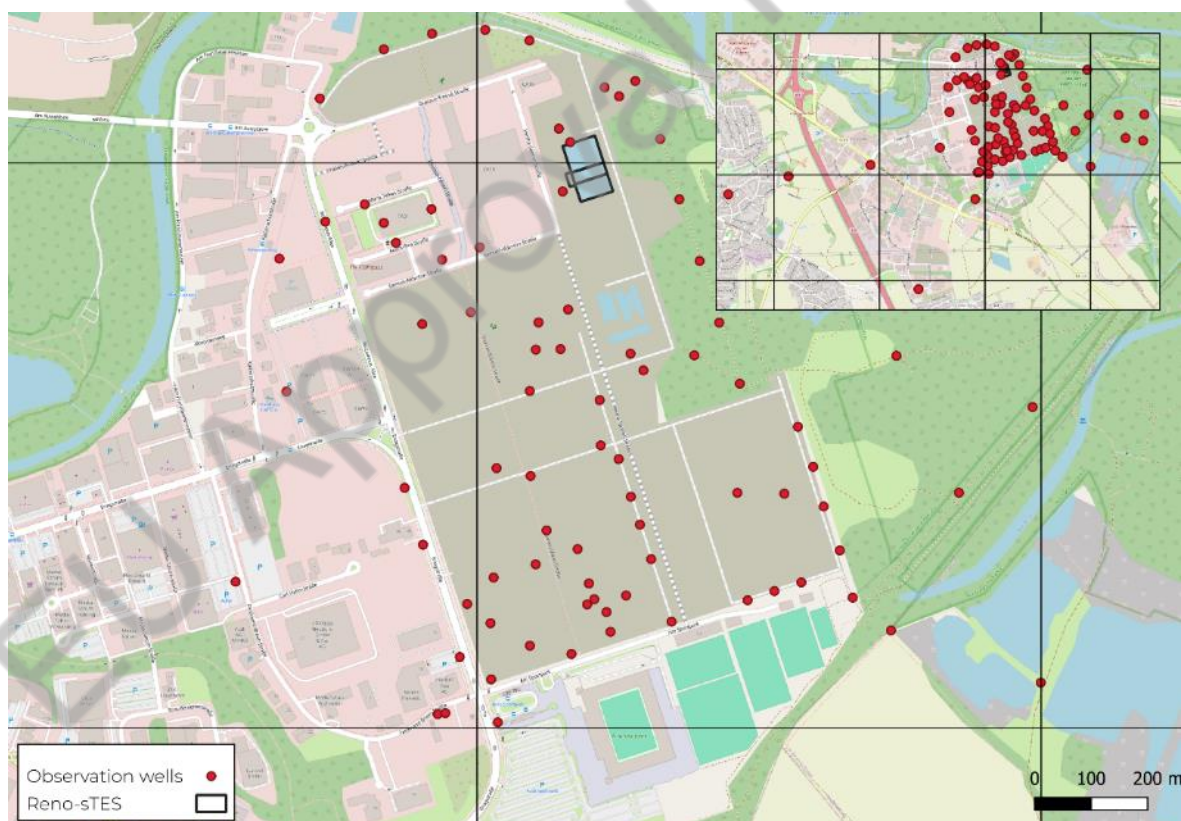


Figure 8: Overview of the key groundwater monitoring wells at the incampus (OpenStreetMap Foundation, 2024; Poser, 2020). Some are already deconstructed, while others are still accessible.

### Groundwater – Levels

Within the city area of Ingolstadt, data on over 1,000 groundwater monitoring wells is managed by the **municipal authorities**. Around 150 measuring points are thereby integrated into a regular measuring program with continuous recordings (via data logger) (Ingolstädter Kommunalbetriebe AöR, 2024). Eight monitoring points (station numbers 79, 88, 91, 716, 926, 2726, 3608, and Fr2 (M. Müller, personal communication, 10 December 2021)) are located in the vicinity of the incampus. Groundwater hydrographs are publicly available for a period of the last 10 - 12 years, and they are integrated into the INTERSTORES monitoring system. If required, longer-term records can be requested (Ingolstädter Kommunalbetriebe AöR, 2024). Further, a groundwater monitoring well of the LfU Bayern (no. 134A) is located 2 km to the west and has been continuously **monitored since 1937** for its groundwater level.

A **spot measurement** to validate a hydrogeological base model (see section above) was carried out in July 2018. It involved measuring over 100 groundwater levels with a vertical height accuracy of 6 cm. Furthermore, between August 2018 and March 2019, the groundwater levels at 10 measuring points in and around the incampus were recorded in high resolution using pressure sensors (loggers) to investigate the transient behaviour of the hydrogeological processes (Poser, 2020). Furthermore, **specific datasets** are available. For example, this is the case for high-resolution data sets for the groundwater monitoring wells “Unterer Donauweg” and “KB03”, which were equipped with loggers for 30 days in 2017, recording the relative development of groundwater levels with an accuracy of 1 mm (R & H Umwelt GmbH, 2024).

### Groundwater – Temperatures

The **municipal authorities** in Ingolstadt (see section above on groundwater levels) additionally monitor groundwater temperatures in the vicinity of the incampus at four measuring points (measuring points no. 3608, 2966, 88, and 86) using data loggers (M. Müller, personal communication, 10 December 2021). These are publicly available and are integrated into INTERSTORES monitoring.

During the year 2022, **monthly sampling campaigns** were carried out at 14 - 55 observation points. This involved taking samples (partly with pumping) and documenting important parameters (temperature, conductivity, pH, oxygen, redox, colour, opacity, and odour). The **sampling protocols** are available and incorporated into the monitoring dataset.

Furthermore, specific datasets for **shorter periods** are available. For example, high-resolution datasets for the groundwater monitoring wells “Unterer Donauweg” and “KB03”, were equipped with loggers for 30 days in the year 2017, and yielded values for groundwater temperature with an accuracy of 0.5 K (R & H Umwelt GmbH, 2024).

Monthly average temperature values from the **downstream protection systems** have been analysed in a preliminary study (Planungsgruppe M+M AG, 2020). Based on the clear seasonality, this data was interpolated to a sinusoidal function ( $T[°C] = -2(0.5233 \cdot t[Months] - 18.34) + 15$ ).

### Groundwater – Quality

The groundwater at the incampus contains small amounts of sulfate, nitrate, phosphate, manganese, and iron. Further, it is mainly oxygen-free, leading to anaerobic conditions and slow degradation of some contaminants. Therefore, quality monitoring is required and existing groundwater monitoring wells are available on the site for this purpose. These measuring points are sampled following a **legally prescribed quality monitoring plan** (Poser, 2020). Although groundwater quality data is not primarily relevant to the subjects and activities of INTERSTORES, the corresponding information can be obtained if required.



### Groundwater – Extracted/Re-infiltrated Quantities

At incampus, water treatment (i.e., purification) of groundwater from sections in the southeast and the southwest, is performed (see “Groundwater Treatment”). Portions of this water are used for thermal energy supply (see “Thermal Exploitation of Groundwater”). Afterwards, infiltration finally follows in specially constructed infiltration trenches and ponds. These processes significantly **influence the water balance** and change groundwater flow directions and velocities, but also temperatures and other parameters (e.g., oxygen content) are altered. An investigation of the infiltration waters in 2022 analysed the **infiltrated water quantities** (Dr. B. Knorr, 2024). The exact positions of the infiltration points are well documented. Quantities of water treatment and infiltration are monitored and available.

### Soil Gases

Control measurements of the soil gas include levels of different contaminants, such as hydrogen sulphide, volatile organic compounds, and aromatic hydrocarbons (BTEX). Oxygen and carbon dioxide levels are determined using on-site measuring devices (Hilgert, 2014). As the remediation activities in this regard are mostly completed and have **no direct impact on the scope of INTERSTORES project contents**, this (historical) data is available but not considered within the project.

### LOX surveillance

To examine the **effects between the underground and the LowEx grid (LOX)** of the incampus, temperature sensors are used both directly in the ground and at the pipeline (Planungsgruppe M+M AG, 2018). Sensors are installed in every section of the grid. Using a steel support structure, the system includes screw-in sensors and ground sensors. Temperature and mass flow (using ultrasound) are measured inside the LOX. The ground measurements (temperature and moisture) are employed on both the supply and return flow of the LOX (Planungsgruppe M+M AG, 2018).

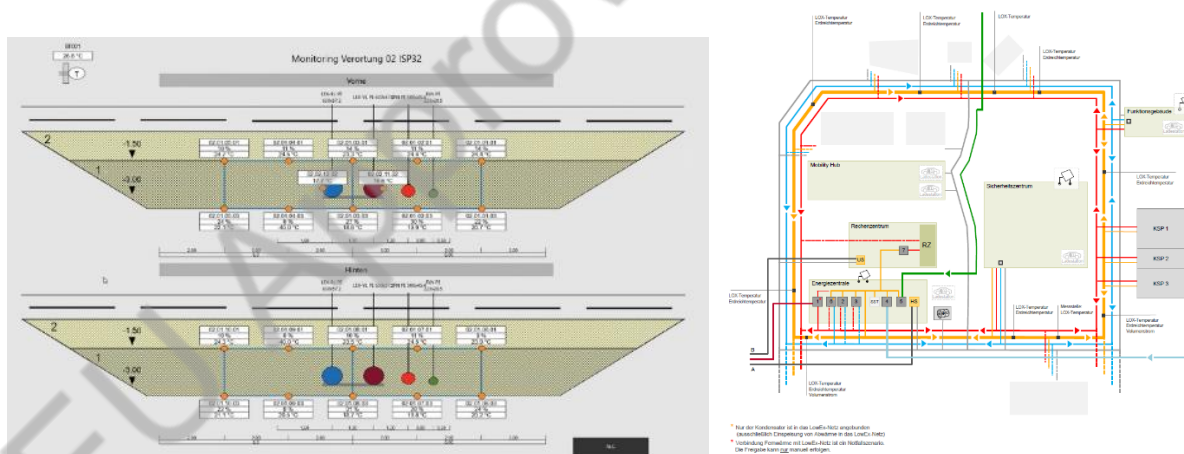


Figure 9: Positions of the sensors for monitoring the surrounding subsurface of the energy supply grid and its pipelines in cross-section (left) and on a schematic overview (right) of the northern part of the incampus (Planungsgruppe M+M AG, 2021b).

#### 4.1.4 Expanded INTERSTORES Monitoring Concept

In the following section, first, the **current design** of the INTERSTORES monitoring concept for the incampus is presented. Second, as examples, two technological aspects of the concept (continuous groundwater monitoring via loggers, and (active) distributed subsurface temperature sensing) are presented as **key methodologies**. In addition, a **detailed site investigation with further methods** conducted in August 2024 forms a fundamental basis for the further optimization of this monitoring concept and is presented in the subsequent section. The monitoring concept at the incampus must be **continuously refined** in line with specific aspects and requirements within the project and in a constant exchange with stakeholders and experts from various domains.

##### Monitoring Concept Description – Summary

**Concept Development.** At the Reno-sTES site on the incampus, the primary objective of the developed monitoring concept is to ensure the **safe and efficient integration of new Reno-sTES/WGTES basins** with the existing infrastructure while minimizing the environmental impact on the surrounding Quaternary sediments. The conceptual framework for the Reno-sTES site includes monitoring the interaction between sTES and the geosphere, with a particular focus on temperature changes. The monitoring concept will also address potential impacts on the hydrosphere, particularly groundwater flow in the area.

**Planning and Implementation.** At the incampus, the site assessment phase involves detailed geological and hydrological studies to understand the conditions of the **existing basin infrastructure** and the surrounding domains. These studies provide the baseline data necessary for designing a monitoring system that can detect temperature changes, and groundwater flow during the operation. The monitoring scheme is designed to capture data from key locations within the sTES and the surrounding environment, including **sensors placed at different depths** within the basins and in the surrounding ground. The installation will include data transmission systems, calibration, and the monitoring system's initialization with reference measurements and calibration equipment.

##### Continuous Groundwater Monitoring

**Technology.** Data loggers for groundwater **temperature and level monitoring** (via hydrostatic pressure) are essential tools for managing water resources. They provide data on both fluctuations, enabling precise environmental analysis in a range of environmental applications, **from ecology studies to thermal transport measurements**. Designed for deployment in various conditions, these devices are critical for general hydrological studies, but also applications in the domain of sTES.

**Requirements.** For accurate monitoring of the groundwater conditions around the Reno-sTES, level measurements must exceed a depth of 3 m, with an accuracy of max. 0.8 cm. The allowed diameter is max. 5 cm for safe deployment in existing wells. For temperatures, the required range is 0 – 40 °C, with an accuracy of max. 0.5 °C. Installed loggers must be capable of recording data at least 1-hour intervals to ensure **harmonized data collection**.

**Equipment.** The foreseen **HOBO U20L Water Level Loggers** (Onset Computer Corporation, 2024) offer precise monitoring of water level and temperature with 0.1% accuracy. Suitable for both groundwater and surface water applications, they are built with durable polypropylene housing for use in freshwater and saltwater environments.

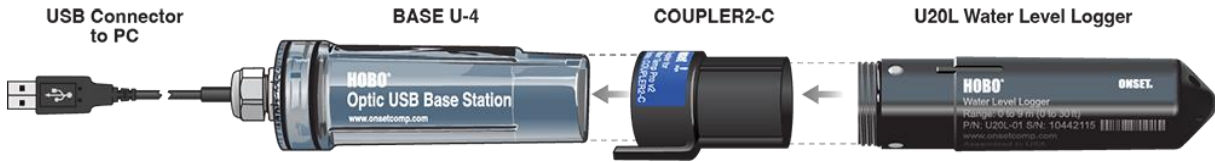


Figure 10: Setup of the data logger system for groundwater levels and temperatures (Onset Computer Corporation, 2024).

Key features include a frost-proof ceramic pressure sensor, operation at depths up to 30 meters, and variable recording rates for critical times like pump operations. A non-vented design ensures easy deployment, with full compensation for barometric pressure, temperature, and water density. Data retrieval is available via an optical USB base station (HOBOT BASE-U-4).

**Spatial Selections.** The current planning includes 17 monitoring points at all sides of the individual sub-basins. In detail, measurements will be recorded both in the corners and in the centre of the sides. Inside each monitoring well, 3-4 loggers will be placed at different heights. The **densified monitoring network** respects the direction of groundwater flow in the southeast, as well as INTERSTORES' research focus on basin C. While temperatures will be recorded at all points, information on groundwater levels is sufficient for 3-4 key locations and can be interpolated.



Figure 11: Current spatial design of the monitoring points for groundwater observation (levels and temperatures) using loggers around the Reno-sTES to be constructed at the incampus (Basemap: OpenStreetMap Foundation, 2024).

### *(Active) Distributed Temperature Sensing*

**Technology.** Distributed Temperature Sensing (DTS) systems measure temperature along an optical fibre over time, providing spatial temperature profiles (REF). Active DTS (aDTS) adds the capability to analyse **thermal transport**, which is useful for monitoring **fluid flow** and characterizing **thermal properties** in situ. This method is especially relevant in hydrogeological applications, where temperature data over time can help determine thermal conductivity and other properties like seepage, soil moisture, and wind speed. aDTS also enables the mapping of thermal transport processes in 2D (Silixa Ltd., 2015, 2022).

**Requirements.** Representative DTS monitoring at the site requires **high responsiveness** to small temperature changes, with flexibility in the design (e.g., options for shortcuts). The system must be highly **resistant to damage** and capable of carrying a static load of several meters of gravel. The DTS must be installed in short, straight sections, with provisions for replacing cables in case of damage. Dry conditions are required at splicing/connector points, and calibration points for both length and temperature are to be considered.

**Equipment.** The **distributed temperature sensor (DTS) system** Silixa XT-DTS is designed for accurate temperature measurements in challenging environments, such as inside and around seasonal thermal energy storage systems. It offers remote configuration and control, with a spatial resolution of 25 cm and temperature resolution of 0.01 K, and can sample data every 5 seconds (Silixa Ltd., 2015; XT-DTS Hardware Manual, 2016). The system includes internal calibration with Pt-100 sensors. The device supports **aDTS measurements using the Heat Pulse System** (Heat Pulse Control System Hardware Manual, 2023) for detailed thermal analysis.

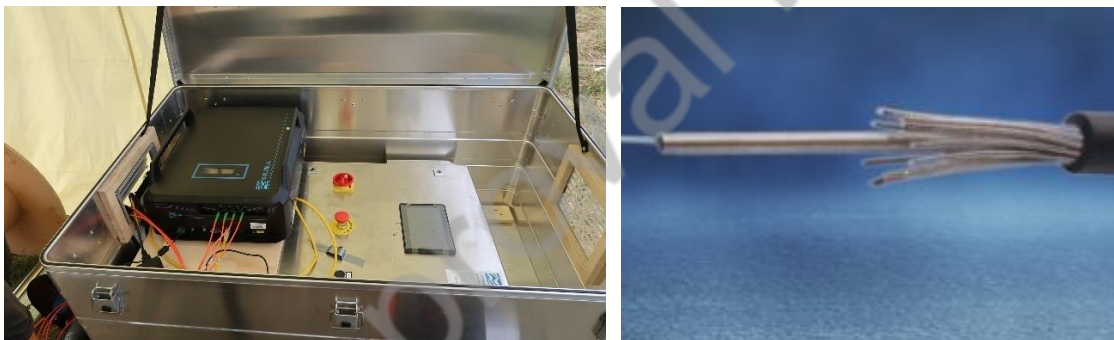


Figure 12: Components of the system for aDTS measurements consisting of the Silixa XT-DTS (black box), the Silixa Heat Pulse System (silver box), and the BRUSens DTS cable (right, for passive DTS measurements) (Right photo: Solifos AG, 2024).

Powered by an electric supply, it provides consistent performance and can be customized to meet specific operational needs (Heat Pulse Control System Hardware Manual, 2023; Heat Pulse System Specification Sheet, 2018). The foreseen **DTS cable** “Solifos BRUSens DTS STL PA” is a robust and flexible fibre optic temperature sensing cable to be used for the ground temperature measurements in the Reno-sTES, and in its surrounding subsurface. It includes stainless steel armored loose tube with four sealed fibres for fast thermal response and high durability. The PA outer sheath protects against abrasion and moisture, while its high crush and tensile strength make it ideal for direct installation in the surrounding sediments (i.e., the gravel). The cable operates without an external power supply, and can thus be used for groundwater flow and thermal transport monitoring.

**Spatial Selection.** The positioning is designed to ensure high-resolution measurements. So far, the planning of the DTS routes focused on the installation within the basins, as the monitoring in the surrounding area will be established later. The spatial selection includes comprehensive coverage of all sub-basins, with **higher coverage for basin C**. Temperature **calibration points** will be placed, and access points will be positioned at every section to facilitate maintenance. A comprehensive description of the detailed monitoring scheme will be provided in Deliverable D4.5 “Energy System Monitoring”. Concerning environmental monitoring, it can be already anticipated that to observe groundwater flow and heat transport processes, the focus will further be placed on the **downstream** side.

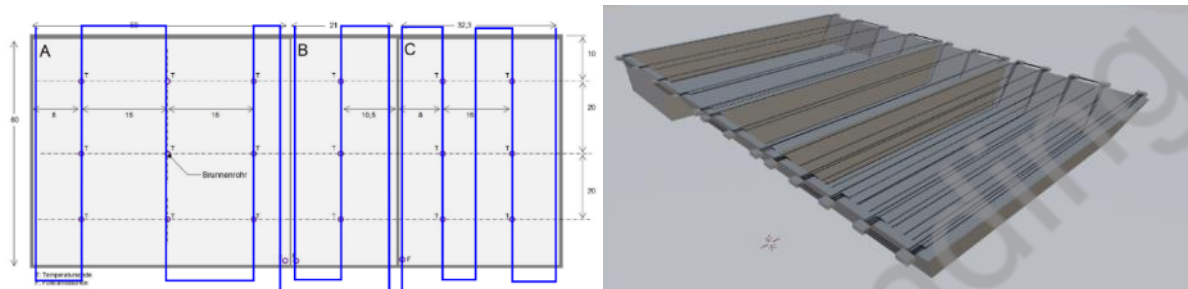


Figure 13: Current spatial design of the monitoring transects for DTS measurements within the basins of the Reno-sTES at the incampus.

#### 4.1.5 Preliminary Results of Initial Monitoring Operation, First Site Investigations, and Analyses of Existing Data

##### Local Geological Setting

The site's geological characteristics have been detailed through dense drill core data and additional resources (Bayerisches Landesamt für Umwelt, 2024b; Dr. W. Knorr, 2018), including the Geological Map of Bavaria. The area shows significant **anthropogenic influence**, with human-made fill reaching depths of over 2.5 m. The upper layers of the subsoil consist of Quaternary, Holocene gravels, ranging in thickness from ca. 4 to 12 meters. These gravels are **highly heterogeneous** both laterally and horizontally, often containing varying amounts of fines and sometimes overlain by alluvial sediments or clays. The variability in thickness is due to the uneven relief of the underlying tertiary topography, which includes **channel structures** running from south to north. Beneath these, the tertiary Upper Freshwater Molasse is composed of highly heterogeneous limnic-fluviatile sediments, primarily sand, silt, and clay, often found in lens-like formations.

##### Local Groundwater Regime

According to the hydrogeological map and a preliminary analysis of data on groundwater levels from existing data sets (Dr. W. Knorr, 2018), the groundwater levels at the incampus are between 360.0 and 361.0 m in elevation. The **groundwater levels typically range between 1 and 4 m** below ground. Aquifer thicknesses of at least 5 meters are expected based on layer thickness and groundwater measurements. The Danube River influences the uppermost aquifer, causing a **groundwater flow predominantly from the W/NW to E/SE**, with an average flow velocity of around 7 meters per day. Historical data indicate groundwater level **fluctuations of nearly one meter** over the past decade (Dr. W. Knorr, 2018).

The aquifer was found a porous, unconfined aquifer. Based on the pumping tests undertaken, permeabilities in the range of  $10^{-2}$  m/s to  $10^{-4}$  m/s have been estimated. Further, it has been assessed as **highly to very highly permeable, with a high porosity of 20 – 30 %**

being assumed (Dr. W. Knorr, 2018). Thermodynamically, a porous aquifer is considered a rather rigid system with a buffering capacity against temperature changes. Concerning seasonality, for example, temporal shifts of one to three months compared to river water and air temperatures are apparent. In historical groundwater temperature data, minimum temperatures fluctuate in a natural range between 8 and 10 °C, while maximum temperatures reach over 15 °C (M. Müller, personal communication, 10 December 2021). The groundwater is thus highly **influenced by the local climate** (precipitation) **and by fluctuating infiltration** from the River Danube (due to water levels) (Dr. W. Knorr, 2018).

### Spot measurement campaign in August 2024

In **August**, MLU undertook its first comprehensive measurement campaign at the incampus site, marking a significant step in understanding the current hydrogeological conditions of the area. The primary aim of this campaign was to evaluate the **status and functionality of the existing wells**, which have undergone various changes due to both landscape changes and extensive remediation efforts over the years. As the site has evolved, some wells have been added to the system to add new nodes to the measurement network, while others have been decommissioned or are no longer functional.

During this campaign, detailed groundwater level measurements were conducted across **75 of the operational wells** to establish a baseline understanding of the current hydrological conditions. In addition to these measurements, **temperature profiles** were recorded in **ten selected wells**. This data is crucial for understanding thermal dynamics in the aquifer, particularly of the ongoing and future energy sTES operations at the site.

Moreover, the campaign included the collection of **fauna samples** from the **same ten wells** where temperature profiles were recorded. These samples will provide insights into the biodiversity and health of the groundwater ecosystem, helping to assess the potential impact of the site's activities on local groundwater fauna. This multi-faceted approach to data collection ensures a comprehensive understanding of the current state of the site, laying the groundwork for ongoing monitoring and future studies.

In addition to the well assessments, a detailed **geophysical screening** was conducted along three sides of the basin, the **east, west, and south perimeters**. This screening was undertaken to gain a more comprehensive understanding of the geological structures around the basin. By mapping the underground features, the screening provides crucial data that will inform the strategic planning and positioning of new groundwater wells.

The geophysical survey is a vital **preparatory step**, as it helps to identify the **most suitable locations for drilling**, ensuring that new wells are optimally placed for both efficiency and minimal environmental impact. This enhanced understanding of underground conditions will not only support the safe and effective drilling of new wells but will also contribute to the broader goal of optimizing the site's overall hydrogeological management.

### **Groundwater Temperature Profiles.**

The Temperature Profiles were recorded in ten of the wells at the incampus site. They were selected based on various factors:

- proximity to the basin
- former contaminated groundwater situation
- depth of the well
- landcover

To conduct precise groundwater temperature measurements, we employed a combination of two advanced instruments: the RBRduet<sup>3</sup> temperature logger (RBR Ltd., 2023) and the KLL-T water level meter equipped with a temperature probe (SEBA Hydrometrie GmbH & Co. KG, 2023). The RBRduet<sup>3</sup> logger, known for its high accuracy of 0.001°C, was securely

attached to the KLL-T meter, which itself has a temperature measurement accuracy of 0.01°C. Together, these instruments were carefully lowered into each well by hand at a controlled speed of approximately 1 cm per second.

As the instruments were descended, the RBRduet<sup>3</sup> continuously recorded the temperature at one-second intervals, capturing a detailed thermal profile of the groundwater column. Concurrently, manual temperature readings were taken every 50 cm to ensure cross-validation of the data and provide additional reference points for analysis.

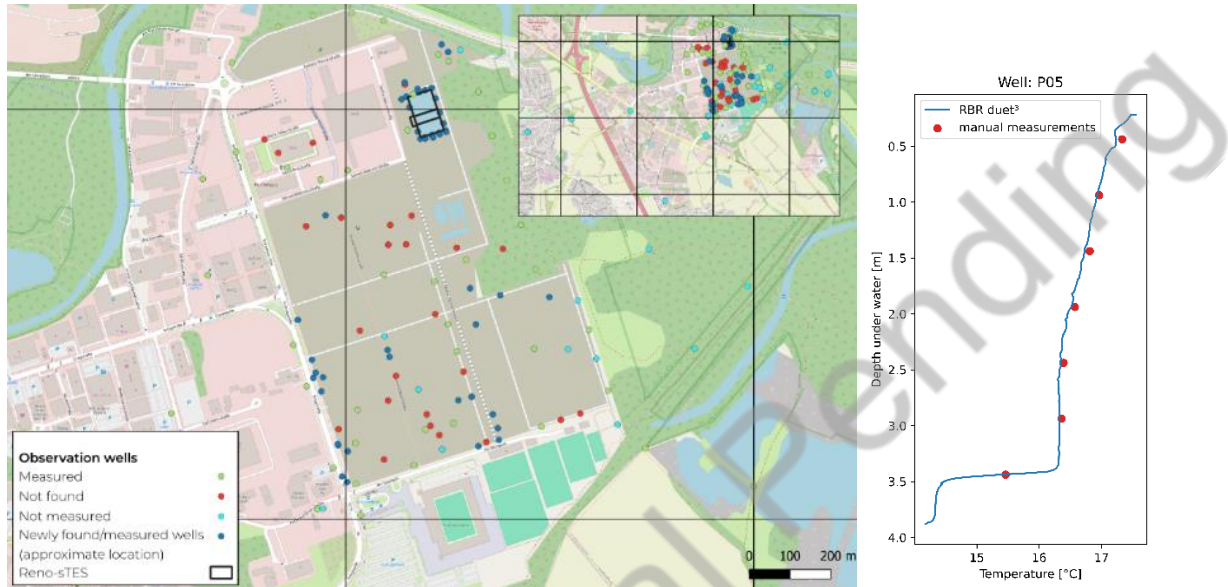


Figure 14: Left: Map of the available monitoring points sampled for groundwater as part of the spot measurement survey by MLU at incampus in August 2024 (OpenStreetMap Foundation, 2024). Right: Preliminary temperature profile of the well P05.

**Geophysical Screening.** An ABEM Terrameter has been used for resistivity surveying. This method is a versatile geophysical method suitable for necessary applications in INTERSTORES, such as geological mapping, groundwater and geothermal prospecting, and geotechnical pre-investigation (Guideline Geo Americas Inc., 2023). A wide range of interpretations will follow such as determining the **depth and thicknesses of subsurface layers** and locating **large deep infrastructure**.

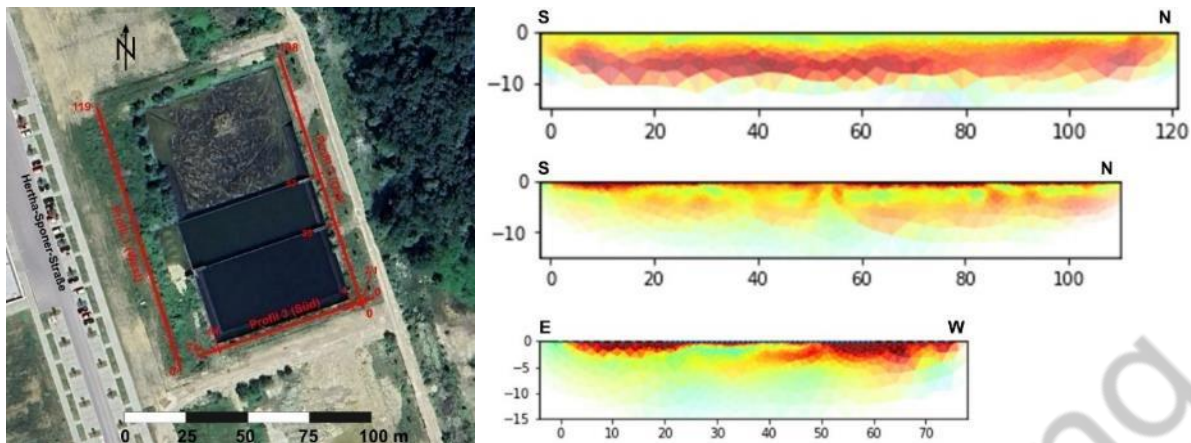


Figure 15: Aerial image with indicated measurement profiles of the geophysical survey at the incampus by MLU in August 2024 (left) and preliminary results (right).

EU Approval Pending

**Groundwater-ecological Screening.** Faunal probing, the process of collecting and analyzing groundwater fauna, is a vital method in ecological monitoring and assessment. Groundwater ecosystems, though often hidden from view, host a wide range of organisms—from **microorganisms to small invertebrates**. These organisms are highly sensitive to environmental changes, making them excellent **bioindicators** for detecting shifts in **groundwater quality, temperature, and chemical composition**. In the context of the incampus project understanding the ecological impacts on the groundwater environment is essential. As the Reno-sTES may influence the thermal conditions of the surrounding groundwater, faunal probing offers a direct measure of these impacts on the subsurface ecosystem. The Reno-sTES interacts closely with the quaternary aquifer. This makes it critical to monitor the response of groundwater fauna to any changes in temperature or other potential stressors introduced by the STES operations. By employing faunal probing methods, it is possible to **track ecological changes over time**, ensuring that the energy storage system operates sustainably without causing harm to the subsurface ecosystems. This approach contributes to a broader understanding of the environmental compatibility of innovative energy technologies with local groundwater ecosystems.

A total of ten fauna samples were collected from the same wells where temperature profiles were recorded, based on the same factors as for the temperature profiles. This approach allows for an independent evaluation of each dataset while also enabling a direct correlation between groundwater temperature profiles and the composition of groundwater fauna.

The sampling is carried out with a **modified Cvetkov net** (Hahn & Fuchs, 2009). It consists of a gauze funnel (mesh size: 73  $\mu\text{m}$ ), which is attached to a collection vessel, specifically a 50 ml centrifuge tube with an added weight. This setup, also called **plankton net**, allows for the efficient collection of small aquatic organisms from the groundwater. This contraption is carefully lowered down to the bottom of a groundwater well with a modified fishing rod. It is then **rapidly raised about 1.5 meters and lowered again**. This process is repeated ten times to stir and capture a wide range of organisms present in the well water column and the well sediments. After a few minutes, the sample is then reduced in water by filtering the probe through a filter with the same mesh as the described gauze funnel. All Material is then washed back into the centrifuge tube with 96% ethanol. This process is used for **fixation to prevent further degradation** (Koch, 2024; Spengler, 2017).

In future steps, it is planned to identify the groundwater fauna by using **Rose Bengal dye** ( $\text{C}_{20}\text{H}_2\text{Cl}_4\text{Na}_2\text{O}_5$  by Thermo Scientific Chemicals). It is added to stain organic matter with a pink hue, enhancing visibility and aiding in the sorting process. The faunal samples are then sorted to the **order level** (Koch, 2024; Spengler, 2017).



## 4.2 VECTES, Vantaa, Finland

### 4.2.1 Site Description

The facility site is in southern Vantaa, southern Finland, close to two busy highways. The bedrock level is near the ground surface, making it ideal for a rock cavern-type facility.

Monitoring began by drilling multiple monitoring wells and deep holes into the bedrock before the construction stage. These are primarily used during construction to monitor groundwater levels and quality, ensuring they do not fall below the accepted levels specified in environmental permits. Monitoring is conducted from the drilled wells as well as privately owned wells around the facility area. There are multiple wells in the area that people use for their everyday water needs. Monitoring the water quality in these privately owned wells is crucial to ensure that construction or operation does not contaminate the groundwater. Groundwater quality is assessed by measuring the concentrations of 20 different elements, pH, oxygen content, oil fraction, and common bacteria and viruses found in the water.

During the construction phase, settlement due to groundwater lowering is also monitored around the facility area. One of the busiest highways in Finland runs above the facility, and any settlement in its structure would be costly. Initially, settlement is monitored only around the above-ground construction site, but once excavation in the bedrock starts, monitoring will be expanded. This is done by inserting settlement studs into the highway structure and regularly measuring their coordinates and levels.

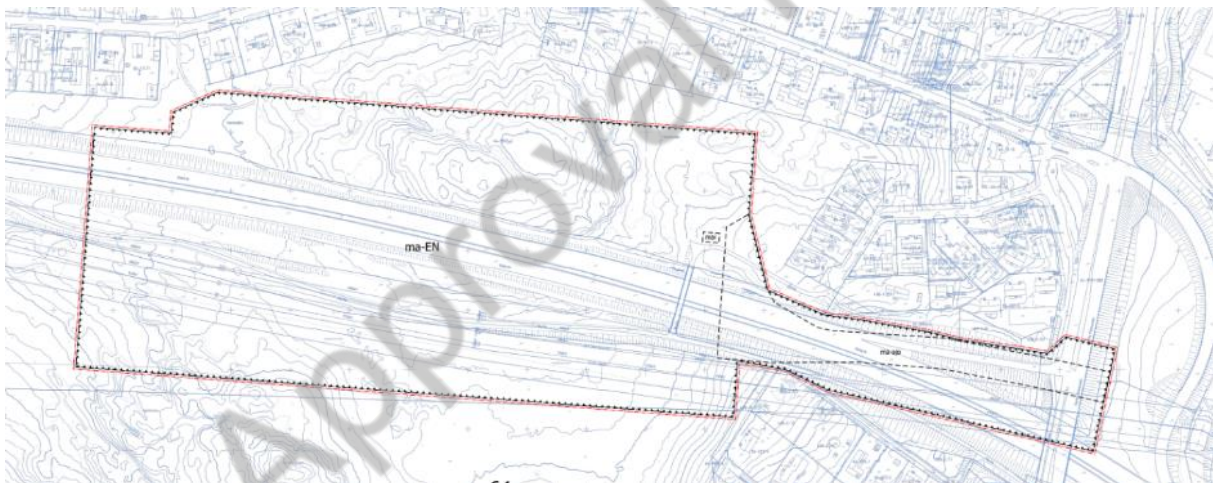


Figure 16: Underground plan area reserved for the facility.

Once construction is completed, the focus will shift to the effects of the facility's operation on the surrounding environment. During the operational phase, it is important to continue monitoring groundwater levels. This is not only to observe changes once the facility is operational but also to adjust facility operations based on groundwater levels and, consequently, the pressure on the facility. To accurately determine which groundwater monitoring points are connected to the facility, groundwater level changes need to be carefully examined during construction and while filling the facility with water. The number of measuring points needed to determine the level and pressure once the facility is operational has not yet been decided.

Additionally, it is anticipated that the facility will likely influence the bedrock once operational. The bedrock will heat up, causing stress changes that might lead to (micro)seismic activity. Seismic monitoring and predictions for the site are still under evaluation. If seismic monitoring is required, basic seismic activity will be monitored during construction to establish a baseline, followed by the installation of geophones around the facility to determine if any seismic activity is caused by the facility's operation.

## 4.2.2 Existing Monitoring Concept

Vantaa Energy has accomplished an environmental impact assessment as part of the Giga-CTES permitting process. This assessment is accepted by environmental authorities and it describes environmental monitoring aspects.

For further site characterisation, existing drill cores will be studied. Samples shall be collected for thermal, mechanical, and hydro tests, roughly 100 samples for thermal analyses, 5 per rock type (in total 25) for mechanical analyses, and 10 for hydro tests.

VECTES site monitoring includes taking groundwater samples, continuous and manual groundwater level measurements, and continuous temperature monitoring. Additionally, fibre optic cables are installed in two drill holes. These cables are used to measure temperature, strain, and acoustic (geophysical) data 4-6 times a year.

For environmental purposes, authorities require that the groundwater levels of bedrock observation wells be measured every second week. Additionally, groundwater samples are taken three times a year, from which hydrocarbons and selected elements are analysed in the laboratory.

At the moment, five point-sensors monitor groundwater levels and temperatures from groundwater observation wells. Additionally, the sensors provide air temperature and pressure data from the site. The sensors collect data every 15 minutes, which is then automatically processed from the server.

### Groundwater monitoring

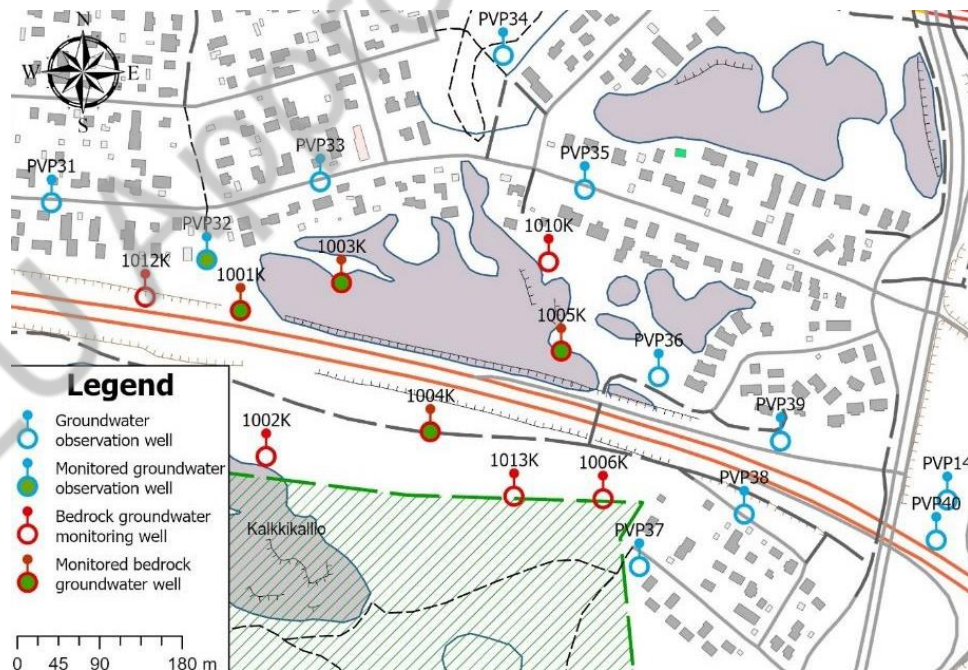


Figure 17. Locations of groundwater observation wells at the VECTES site.

The existing wells around VECTES can be seen in Figure 17. Locations of groundwater observation wells at the VECTES site. Figure 17. The blue-marked wells have a depth of around ten meters and end in the Quarternary sediments. The red-marked wells are deeper and have a depth of 40 to 150 meters. For continuous monitoring, several wells are equipped with data loggers. These wells are marked green on the map. Wells PVP32 and 1001K are equipped with Keller-Druck PR-26D and well 1004K with Keller-Druck PAA-26X sensors to monitor the groundwater level as well as the temperature with a maximum deviation of 1 % (Keller Druckmesstechnik AG, 2023). Wells 1003K and 1005K are equipped with Van Essen TD-Diver sensors for groundwater level and temperature with an accuracy of 0.2 cm/0.01 °C (Figure 18) (Van Essen Instruments B.V., 2024).



Figure 18. Left: Installed remote access groundwater sensor in the groundwater observation well at the VECTES site. Right: Van Essen Diver sensors.

Summary

Table 1. Summary of the VECTES default monitoring setup.

Sensor type	Location	Purpose	Unit	Range
Manual measurements	21 holes drilled by the project and 20 privately owned wells around the project area	groundwater level monitoring		
Groundwater quality samples	7 wells and 2 deep rock holes around the project area	groundwater quality monitoring		every 4 months
studs measured by hand	11 measurement points around the construction site	settlement measurements on the road	coordinates (x,y,z)	every 3 months

### 4.2.3 Expanded INTERSTORES Monitoring Concept

#### Monitoring Concept Description – Summary

**Concept Development.** At the Giga-CTES site, the monitoring concept is designed to address the unique challenges of storing thermal energy in a cavern excavated from solid bedrock. The primary objective of the monitoring concept at this site is to ensure the **stability and integrity** of the rock formations. The conceptual framework includes monitoring subsurface temperature and pressure changes, as well as the interaction between the filling and the surrounding rock formations, including interactions with fractures. The selection of methods and technologies must focus on sensors capable of withstanding the **adverse conditions** in and/or near the cavern, including high temperatures and pressures.

**Planning & Implementation.** The site assessment phase at the VECTES in Finland involves detailed geological studies to understand the characteristics of the **rock formations**. These studies provide the baseline data necessary for designing a monitoring system that can detect changes in temperature, pressure, and geomechanical stresses. The installation phase will consider the spatial **heterogeneity** (e.g., fractured zones) of the rock formations. The monitoring scheme is designed to capture data from key locations within the cavern and the surrounding rock formations, to monitor temperature gradients and at key locations within the surrounding rock. The initialization involves analyses of expected temperature ranges and the time scales over which changes are likely to occur during the operation of the CTES.

#### Distributed measurements

Surrounding drill holes are planned to be utilized for distributed sensing measurements, including temperature, strain, and acoustic sensing. Possible drill holes are located in the western, northern, and eastern sides of the designed storage facility. The deployed cable includes multimode and single-mode fibres that are applicable for distributed temperature sensing (DTS), distributed strain sensing (DSS), and distributed acoustic sensing (DAS) measurements.

Distributed temperature sensing will provide valuable information about temperature changes over the depth. The Silixa XT-DTS will be utilized for that with a spatial resolution of 0.25 meters and an accuracy of up to 0.1 °C (Silixa Ltd., 2015).

Additionally, the distributed strain sensing method can provide data on how much thermal strain affects specific positions with the Silixa iDSS with a strain resolution of < 1  $\mu\epsilon$ , a sampling resolution of 0.1 meters with a spatial resolution of minimum 0.6 meters (Silixa Ltd., 2024a).

The geophysical distributed acoustic sensing method might provide information on whether any changes occur in fractures in the bedrock. The Silixa iDAS with a resolution of ten meters and an acoustic sensitivity of 0.001 up to 50 Hz is used for that purpose (Silixa Ltd., 2024b).

In the initial phase, cables for distributed sensing can be installed in existing drill holes. However, once the storage facility is excavated, distributed sensing cables can be installed within the excavated facility, providing kilometres of data from the facility.



Figure 19. Potential locations for distributed sensing measurements around the VECTES caverns. The fibre optic cables can be installed in the caverns after the excavations have been completed.

Additional preliminary ideas for monitoring

- Installing more continuous groundwater level sensors
- Heat flow, and pressure sensors in the facility once it has been constructed.
- Sampling algae and bacteria which indicate thermal fluctuations from the nearby groundwater monitoring wells once the thermal storage is in operation and see if heating subsurface affects algae and thermally affected bacteria in groundwater.

Table 2. Summary of the INTERSTORES-specific monitoring setup at the VECTES site.

Sensor type	Location	Purpose	Unit
Geophone	2 measuring points on both sides of the facility	measuring seismic activity on site while the facility is operational	magnitude
automatic groundwater level sensor	around the facility	measuring the effect operating the facility has on the areas' groundwater and if changes in the operation are needed	mm
DTS, DSS & DAS	around the facility	Measuring temperature, strain and acoustic signals within the surrounding subsurface	K, m/m, dB

## 5 Summary & Outlook

This report provided a comprehensive overview of environmental monitoring concepts for the two sTES systems of the INTERSTORES project: the Reno-sTES at incampus in Ingolstadt, Germany, and the Giga-CTES in Vantaa, Finland. The INTERSTORES project, funded by the Horizon 2020 Innovation Action (IA) Program, aimed to advance sTES technologies by enhancing their integration into existing energy infrastructures, reducing costs, and improving their overall environmental and economic viability.

The report illustrated how the Reno-sTES and Giga-CTES facilities differ significantly in terms of their design, scale, and development status. The Reno-sTES facility utilized existing basin infrastructure at a redeveloped industrial site, demonstrating a cost-effective approach through the reuse of existing water reservoirs and alignment with circular economy principles. Conversely, the Giga-CTES site involves the building of a new large-scale storage facility within a rock cavern, highlighting an approach focused on economies of scale for substantial storage capacity.

While the storage facilities differ in design and scale, both of them interact with their surrounding environment, necessitating careful monitoring and understanding of their respective impacts. The geological and environmental conditions at the sites also differ significantly. The Reno-sTES is located within the shallow Danube aquifer, while the Giga-CTES is situated within a fractured rock formation. These distinct geological contexts require tailored monitoring approaches, adapted to the specific characteristics and challenges of each site.

The report outlined the foundational aspects of monitoring, emphasizing the importance of data collection, technological integration, and adapting monitoring approaches to specific site conditions. The Reno-sTES site, being more advanced in the development of its storage facility, provided detailed insight into the interactions between the storage system and its surrounding environment, particularly concerning groundwater, temperature profiles, and local fauna. In contrast, the Giga-CTES site, still in earlier stages of sTES facility development, presented a different set of challenges and opportunities, requiring distinct monitoring techniques suited to its unique geological setting.

The report showed how tailored monitoring strategies are essential for ensuring safe, sustainable, and efficient sTES operations. It highlighted how these strategies were applied at both demonstration sites to measure local environmental effects, optimize system performance, and build public confidence. Furthermore, it identified generally applicable monitoring concepts that could be transferred to other sTES projects, emphasizing the need for continuous innovation and adaptability in environmental monitoring practices.

Ultimately, this report provided valuable insights into the practical challenges and opportunities associated with sTES deployment, demonstrating that the effectiveness of environmental monitoring concepts depends heavily on the specific characteristics and development status of each site. Looking ahead, the monitoring concepts for both the Reno-sTES and Giga-CTES sites remain in their early stages and may need to adapt as project plans evolve or new findings emerge. As the development of these facilities progresses, unexpected changes in environmental conditions, technological requirements, or operational practices may necessitate adjustments in the monitoring strategies.

This flexibility is essential to ensure that environmental monitoring remains effective, relevant, and capable of capturing all critical data. Future efforts will need to remain open to incorporating new insights and adapting to evolving circumstances, ensuring that the monitoring framework is robust enough to respond to the dynamic nature of both sites. By maintaining this adaptive approach, the project will better safeguard environmental integrity while optimizing the performance of the sTES systems.

## 6 References

- ARCADIS Deutschland GmbH. (2010). *Hydrogeologisches Standortmodell + numerisches Grundwassermodell Teil 1 Hydrogeologisches Standortmodell*.
- Audi Planung GmbH. (2022). *Incampus Strukturplan* [Map].
- Bauer, S., Dahmke, A., & Kolditz, O. (2017). Subsurface energy storage: Geological storage of renewable energy-capacities, induced effects and implications. *ENVIRONMENTAL EARTH SCIENCES*, 76(20), 695. <https://doi.org/10.1007/s12665-017-7007-9>
- BauGrund Süd Gesellschaft für Geothermie mbH. (2022). *Bohrdokumentation AZA2112016*.
- Bayer, P., & Finkel, M. (2006). Life cycle assessment of active and passive groundwater remediation technologies. *Journal of Contaminant Hydrology*, 83(3), 171–199. <https://doi.org/10.1016/j.jconhyd.2005.11.005>
- Bayerisches Landesamt für Umwelt. (2023). *Digitale Geologische Karte von Bayern 1:25.000 (dGK25) Erläuterungen zu Vektordatensatz und Visualisierung*.
- Bayerisches Landesamt für Umwelt. (2024a). *Hydrogeologische Karte 1:50.000—LfU Bayern* [Dataset]. [https://www.lfu.bayern.de/geologie/hydrogeologie\\_karten\\_daten/hk50/index.htm](https://www.lfu.bayern.de/geologie/hydrogeologie_karten_daten/hk50/index.htm)
- Bayerisches Landesamt für Umwelt. (2024b). *UmweltAtlas Bayern* [Dataset]. <https://www.umweltatlas.bayern.de>
- Becher, J., Englisch, C., Griebl, C., & Bayer, P. (2022). Groundwater fauna downtown – Drivers, impacts and implications for subsurface ecosystems in urban areas. *Journal of Contaminant Hydrology*, 248, 104021. <https://doi.org/10.1016/j.jconhyd.2022.104021>
- Bergmann, P., Schmidt-Hattenberger, C., Kiessling, D., Ruecker, C., Labitzkel, T., Henniges, J., Baumann, G., & Schuett, H. (2012). Surface-downhole electrical resistivity tomography applied to monitoring of CO<sub>2</sub> storage at Ketzin, Germany. *GEOPHYSICS*, 77(6), B253–B267. <https://doi.org/10.1190/GEO2011-0515.1>
- Blum, P., Menberg, K., Koch, F., Benz, S. A., Tissen, C., Hemmerle, H., & Bayer, P. (2021). Is thermal use of groundwater a pollution? *Journal of Contaminant Hydrology*, 239, 103791. <https://doi.org/10.1016/j.jconhyd.2021.103791>
- Bock, H. (1994). Recent developments in in-situ testing and performance monitoring of soil and rock structures. In *Developments in Geotechnical Engineering: From Harvard to New Delhi 1936-1994*. CRC Press.
- Bolton, R., Cameron, L., Kerr, N., Winkler, M., & Desguers, T. (2023). Seasonal thermal energy storage as a complementary technology: Case study insights from Denmark and The Netherlands. *Journal of Energy Storage*, 73, 109249. <https://doi.org/10.1016/j.est.2023.109249>
- Bott, C., Dressel, I., & Bayer, P. (2019). State-of-technology review of water-based closed seasonal thermal energy storage systems. *RENEWABLE & SUSTAINABLE ENERGY REVIEWS*, 113, 109241. <https://doi.org/10.1016/j.rser.2019.06.048>
- Brielmann, H., Griebl, C., Schmidt, S. I., Michel, R., & Lueders, T. (2009). Effects of thermal energy discharge on shallow groundwater ecosystems. *FEMS Microbiology Ecology*, 68(3), 273–286. <https://doi.org/10.1111/j.1574-6941.2009.00674.x>
- Brielmann, H., Lueders, T., Schreglmann, K., Ferraro, F., Avramov, M., Hammerl, V., Blum, P., Bayer, P., & Griebl, C. (2011). Oberflächennahe Geothermie und ihre potenziellen Auswirkungen auf Grundwasserökosysteme. *Grundwasser*, 16(2), 77–91. <https://doi.org/10.1007/s00767-011-0166-9>
- Butean, A., Butean, D., Vladu, I., & Sorostinean, M. (2024). *Data Management Plan* [Deliverable D1.1 of INTERSTORES (unpublished)].
- Butler Jr., J. J. (1990). The Role of Pumping Tests in Site Characterization: Some Theoretical Considerations. *Ground Water*, 28(3), 394–402. <https://doi.org/10.1111/j.1745-6584.1990.tb02269.x>



- Butscher, C., Mutschler, T., & Blum, P. (2016). Swelling of Clay-Sulfate Rocks: A Review of Processes and Controls. *ROCK MECHANICS AND ROCK ENGINEERING*, 49(4), 1533–1549. <https://doi.org/10.1007/s00603-015-0827-6>
- Coscia, I., Greenhalgh, S. A., Linde, N., Doetsch, J., Marescot, L., Guenther, T., Vogt, T., & Green, A. G. (2011). 3D crosshole ERT for aquifer characterization and monitoring of infiltrating river water. *GEOPHYSICS*, 76(2), G49–G59. <https://doi.org/10.1190/1.3553003>
- Cultrera, M., Boaga, J., Di Sipio, E., Dalla Santa, G., De Seta, M., & Galgaro, A. (2018). Modelling an induced thermal plume with data from electrical resistivity tomography and distributed temperature sensing: A case study in northeast Italy. *HYDROGEOLOGY JOURNAL*, 26(3), 837–851. <https://doi.org/10.1007/s10040-017-1700-3>
- Dahash, A., Ochs, F., Janetti, M. B., & Streicher, W. (2019). Advances in seasonal thermal energy storage for solar district heating applications: A critical review on large-scale hot-water tank and pit thermal energy storage systems. *APPLIED ENERGY*, 239, 296–315. <https://doi.org/10.1016/j.apenergy.2019.01.189>
- Dai, F., Li, B., Xu, N., Fan, Y., & Zhang, C. (2016). Deformation forecasting and stability analysis of large-scale underground powerhouse caverns from microseismic monitoring. *INTERNATIONAL JOURNAL OF ROCK MECHANICS AND MINING SCIENCES*, 86, 269–281. <https://doi.org/10.1016/j.ijrmms.2016.05.001>
- Daniels, J. (2000). *Ground Penetrating Radar Fundamentals*. <https://doi.org/10.4133/1.2921864>
- De Simone, S., Vilarrasa, V., Carrera, J., Alcolea, A., & Meier, P. (2013). Thermal coupling may control mechanical stability of geothermal reservoirs during cold water injection. *Physics and Chemistry of the Earth*, 64, 117–126. <https://doi.org/10.1016/j.pce.2013.01.001>
- Deutscher Wetterdienst. (2017). *Handbuch Ortsgenaue Testreferenzjahre von Deutschland für mittlere, extreme und zukünftige Witterungsverhältnisse*.
- Deutscher Wetterdienst. (2024). *Climate Data Center* (Version CDC-v2.1.b22.09) [Dataset]. <https://cdc.dwd.de/portal/>
- DIN 4022-1:1987-09 *Baugrund und Grundwasser; Benennen und Beschreiben von Boden und Fels; Schichtenverzeichnis für Bohrungen ohne durchgehende Gewinnung von gekernten Proben im Boden und im Fels*. (1987). DIN Media GmbH. <https://www.dinmedia.de/de/norm/din-4022-1/1358651>
- Einarson, M. D., & Cherry, J. A. (2002). A New Multilevel Ground Water Monitoring System Using Multichannel Tubing. *Groundwater Monitoring & Remediation*, 22(4), 52–65. <https://doi.org/10.1111/j.1745-6592.2002.tb00771.x>
- Everett, M. E. (2013). *Near-Surface Applied Geophysics*. Cambridge University Press. <https://doi.org/10.1017/CBO9781139088435>
- Faigl, M., & Göttl, K. (2019). *incampus—Innovative Technologien, Smarte Energie*. AUDI Werksplanung/Planung Energie und Gebäudetechnik.
- Fernandes, I., & Chaminé, H. I. (2023). In Situ Geotechnical Investigations. In C. Chastre, J. Neves, D. Ribeiro, M. G. Neves, & P. Faria (Eds.), *Advances on Testing and Experimentation in Civil Engineering: Geotechnics, Transportation, Hydraulics and Natural Resources* (pp. 29–54). Springer International Publishing. [https://doi.org/10.1007/978-3-031-05875-2\\_2](https://doi.org/10.1007/978-3-031-05875-2_2)
- Gonzalez-Ayala, J., Blazquez, C. S., Laguela, S., & Nieto, I. M. (2024). Assessment for optimal underground seasonal thermal energy storage. *ENERGY CONVERSION AND MANAGEMENT*, 308, 118394. <https://doi.org/10.1016/j.enconman.2024.118394>
- Griebler, C., Brielmann, H., Haberer, C. M., Kaschuba, S., Kellermann, C., Stumpp, C., Hegler, F., Kuntz, D., Walker-Hertkorn, S., & Lueders, T. (2016). Potential impacts of geothermal energy use and storage of heat on groundwater quality, biodiversity, and ecosystem processes. *ENVIRONMENTAL EARTH SCIENCES*, 75(20), 1391. <https://doi.org/10.1007/s12665-016-6207-z>



- Guideline Geo Americas Inc. (2023). *ABEM Terrameter LS 2* [Brochure]. <https://www.guidelinegeoc.cdn.triggerfish.cloud/uploads/2017/08/ABEM-Terrameter-LS-2-Brochure-210823-web.pdf>
- Hahn, H. J., & Fuchs, A. (2009). Distribution patterns of groundwater communities across aquifer types in south-western Germany. *Freshwater Biology*, 54(4), 848–860. <https://doi.org/10.1111/j.1365-2427.2008.02132.x>
- Hawkins, A. J., Becker, M. W., & Tsoflias, G. P. (2017). Evaluation of inert tracers in a bedrock fracture using ground penetrating radar and thermal sensors. *GEOTHERMICS*, 67, 86–94. <https://doi.org/10.1016/j.geothermics.2017.01.006>
- Heat Pulse Control System Hardware Manual*. (2023). Silixa Ltd.
- Heat Pulse System Specification Sheet*. (2018). Silixa Ltd. <https://silixa.com/wp-content/uploads/Heat-Pulse-System-Specification-Sheet.pdf>
- Heldt, S., Wang, B., & Bauer, S. (2023). Parameter identification and range restriction through sensitivity analysis for a high-temperature heat injection test. *Geothermal Energy*, 11(1), 12. <https://doi.org/10.1186/s40517-023-00255-5>
- Hilgert, Dr. W. (2014). *Ehem. Gelände der Bayernoil Raffinerie GmbH Ingolstadt- Teilflächen 3 und 5—Zusammenfassung und Präzisierung des Sanierungsplans*. R & H Umwelt GmbH.
- Hochwassernachrichtendienst Bayern. (2024a). *Pegel Ingolstadt Luitpoldstraße / Donau* [Dataset]. [https://www.hnd.bayern.de/pegel/donau\\_bis\\_kelheim/ingolstadt-luitpoldstrasse-10046105/tabelle?methode=wasserstand&days=365](https://www.hnd.bayern.de/pegel/donau_bis_kelheim/ingolstadt-luitpoldstrasse-10046105/tabelle?methode=wasserstand&days=365)
- Hochwassernachrichtendienst Bayern. (2024b). *Wasserstand: Aktuelle Messwerte Niederstimm / Sandrach* [Dataset]. <https://www.gkd.bayern.de/de/fluesse/wasserstand/kelheim/niederstimm-13241005/messwerte>
- Ingolstädter Kommunalbetriebe AöR. (2024). *Grundwasserbeobachtung und Messprogramme* [Dataset]. <https://www.in-kb.de/Wasser/Grundwasser/Grundwasserbeobachtung-und-Messstellen/>
- Jackson, T. J. (2002). Remote sensing of soil moisture: Implications for groundwater recharge. *HYDROGEOLOGY JOURNAL*, 10(1), 40–51. <https://doi.org/10.1007/s10040-001-0168-2>
- Jiang, Z., Ringel, L. M., Bayer, P., & Xu, T. (2023). Fracture Network Characterization in Reservoirs by Joint Inversion of Microseismicity and Thermal Breakthrough Data: Method Development and Verification. *Water Resources Research*, 59(9), e2022WR034339. <https://doi.org/10.1029/2022WR034339>
- Keller Druckmesstechnik AG. (2023). *Keller Serie 26Y Piezoresistive Pegelsonde mit hoher Genauigkeit* [Datenblatt]. <https://download.keller-druck.com/api/download/6YobYEAZR5GjyERxufhNLI/de/2023-04.pdf>
- Knorr, Dr. B. (2024). *Temperatur-Monitoring zur abströmigen Überwachung des Sickerwassergrabens und Gewässer im Auwald Kälberschütt* (p. 18). Ingenieurbüro Dr. Knorr GmbH.
- Knorr, Dr. W. (2018). Audi AG / IN-Campus GmbH Vorstudie über die thermische Grundwassernutzung über Horizontalfilterbrunnen. *Ing. Büro Dr. Knorr GmbH*.
- Koch, F. (2024). *Spatial and temporal analysis of groundwater ecosystems*. Karlsruhe Institute of Technology.
- Lakhankar, T., Ghedira, H., Temimi, M., Sengupta, M., Khanbilvardi, R., & Blake, R. (2009). Non-parametric Methods for Soil Moisture Retrieval from Satellite Remote Sensing Data. *REMOTE SENSING*, 1(1), 3–21. <https://doi.org/10.3390/rs1010003>
- Landesamt für Digitalisierung, Breitband und Vermessung. (2024). *3D Geländemodell Bayern* [Dataset]. <https://www.ldbv.bayern.de/produkte/3dprodukte/gelaende.html>
- Leven, C., & Dietrich, P. (2006). What information can we get from pumping tests? - Comparing pumping test configurations using sensitivity coefficients. *JOURNAL OF HYDROLOGY*, 319(1–4), 199–215. <https://doi.org/10.1016/j.jhydrol.2005.06.030>



- Lewin, I., Drefke, C., Piepenbrink, M., Schueth, C., & Hoppe, A. (2014). Determination of the hydraulic conductivity of Quaternary sediments by means of sieve analyses and pumping tests. *GRUNDWASSER*, 19(2), 127–135. <https://doi.org/10.1007/s00767-014-0253-9>
- Liu, W., Li, Q., Yang, C., Shi, X., Wan, J., Jurado, M. J., Li, Y., Jiang, D., Chen, J., Qiao, W., Zhang, X., Fan, J., Peng, T., & He, Y. (2023). The role of underground salt caverns for large-scale energy storage: A review and prospects. *Energy Storage Materials*, 63, 103045. <https://doi.org/10.1016/j.ensm.2023.103045>
- Lyden, A., Brown, C. S., Kolo, I., Falcone, G., & Friedrich, D. (2022). Seasonal thermal energy storage in smart energy systems: District-level applications and modelling approaches. *Renewable and Sustainable Energy Reviews*, 167, 112760. <https://doi.org/10.1016/j.rser.2022.112760>
- Müller, M. (2021, December 10). *Grundwasserstandsdaten Ingolstädter Kommunalbetriebe* [Personal communication].
- Nilsson, E., & Rohdin, P. (2019). Performance evaluation of an industrial borehole thermal energy storage (BTES) project—Experiences from the first seven years of operation. *RENEWABLE ENERGY*, 143, 1022–1034. <https://doi.org/10.1016/j.renene.2019.05.020>
- Noethen, M., Hemmerle, H., & Bayer, P. (2023). Sources, intensities, and implications of subsurface warming in times of climate change. *CRITICAL REVIEWS IN ENVIRONMENTAL SCIENCE AND TECHNOLOGY*, 53(5), 700–722. <https://doi.org/10.1080/10643389.2022.2083899>
- Nordbeck, J., Bauer, S., Dahmke, A., Delfs, J.-O., Gomes, H., Hailemariam, H., Kinias, C., zu Beerentrup, K. M., Nagel, T., Smirr, C., Vienken, T., Wuttke, F., & Beyer, C. (2020). A modular cement-based subsurface heat storage: Performance test, model development and thermal impacts. *APPLIED ENERGY*, 279, 115823. <https://doi.org/10.1016/j.apenergy.2020.115823>
- Nußbicker-Lux, J., Bauer, D., Marx, R., Heidemann, W., & Müller-Steinhagen, H. (2009). *MONITORING RESULTS FROM GERMAN CENTRAL SOLAR HEATING PLANTS WITH SEASONAL THERMAL ENERGY STORAGE*.
- Onset Computer Corporation. (2024). *HOBO® U20L Water Level Logger (U20L-0x) Manual*.
- OpenStreetMap Foundation. (2024). *OpenStreetMap* [Open Data Commons Open Database-License]. <https://www.openstreetmap.org/>
- Pavlov, G., & Olesen, B. W. (2012). Thermal energy storage - A review of concepts and systems for heating and cooling applications in buildings: Part 1 - Seasonal storage in the ground. *HVAC&R RESEARCH*, 18, 515–538. <https://doi.org/10.1080/10789669.2012.667039>
- Planungsgruppe M+M AG. (2018). *IN-Campus Positionierung Messtechnik LowEx*.
- Planungsgruppe M+M AG. (2020). *Monatliche Brunnentemperaturen IN-Campus* [Unpublished].
- Planungsgruppe M+M AG. (2021a). *Beschreibung Energiekonzept*.
- Planungsgruppe M+M AG. (2021b). *LowEx BA1 Planungsstand Uebersicht Schema*.
- Planungsgruppe M+M AG. (2023). *Audi InCampus—Energiezentrale (BB15-162-12)* [Ausschreibung].
- Poser, Dr. A. (2020). *IN-Campus Gelände Ingolstadt Grundwassermodellmodell Validierung und instationäre Kalibrierung Gutachten*. ARGE N+R c/o: R & H Umwelt GmbH.
- Qin, Z. H., Berliner, P., & Karnieli, A. (2002). Numerical solution of a complete surface energy balance model for simulation of heat fluxes and surface temperature under bare soil environment. *APPLIED MATHEMATICS AND COMPUTATION*, 130(1), 171–200. [https://doi.org/10.1016/S0096-3003\(01\)00089-3](https://doi.org/10.1016/S0096-3003(01)00089-3)
- R & H Umwelt GmbH. (2024). *Loggerdaten Grundwassermessstellen unterer Donauweg* [Unpublished].
- RBR Ltd. (2023). *RBRduet<sup>3</sup> Datasheet*.




- SEBA Hydrometrie GmbH & Co. KG. (2023). *KLL, KLL-T, KLL-Mini, TLG* [Prospekt]. <https://pdf.directindustry.de/pdf/seba-hydrometrie-gmbh-co-kg/kll-kll-t-kll-mini-tlg/63216-817709.html>
- Selker, J. S., Thévenaz, L., Huwald, H., Mallet, A., Luxemburg, W., van de Giesen, N., Stejskal, M., Zeman, J., Westhoff, M., & Parlange, M. B. (2006). Distributed fiber-optic temperature sensing for hydrologic systems. *Water Resources Research*, 42(12). <https://doi.org/10.1029/2006WR005326>
- Silixa Ltd. (2015). *XT-DTS Datasheet*. <https://silixa.com/technology/xt-dts/>
- Silixa Ltd. (2022). *Introduction to Distributed Temperature Sensing*. <https://silixa.com/wp-content/uploads/DTS-Primer-2022.pdf>
- Silixa Ltd. (2024a). *Distributed Strain Sensor | iDSS™*. <https://silixa.com/technology/idss-intelligent-distributed-strain-sensor/>
- Silixa Ltd. (2024b). *iDAS intelligent Distributed Acoustic Sensor* [Datasheet]. [https://silixa.com/wp-content/uploads/iDAS\\_Datasheet\\_2024.pdf](https://silixa.com/wp-content/uploads/iDAS_Datasheet_2024.pdf)
- Solifos AG. (2024, January 16). *BRUmil Kabel von Solifos AG erhalten die VG Zulassung des VDE*. <https://solifos.com/brumil-kabel-von-solifos-ag-erhalten-die-vg-zulassung-des-vde/>
- Spengler, C. (2017). *Die Auswirkungen von anthropogenen Temperaturerhöhungen auf die Crustaceagemeinschaften im Grundwasser—Versuch einer Prognose zur Klimaerwärmung und lokalen Wärmeeinträgen*. <https://kola.opus.hbz-nrw.de/frontdoor/index/index/docId/1554>
- Stauffer, F., Bayer, P., Blum, P., Giraldo, N. M., & Kinzelbach, W. (2013). *Thermal Use of Shallow Groundwater*. CRC Press. <https://doi.org/10.1201/b16239>
- Stemmler, R., Hanna, R., Menberg, K., Ostergaard, P. A., Jackson, M., Staffell, I., & Blum, P. (2024). Policies for aquifer thermal energy storage: International comparison, barriers and recommendations. *CLEAN TECHNOLOGIES AND ENVIRONMENTAL POLICY*. <https://doi.org/10.1007/s10098-024-02892-1>
- Thomas, G., Demski, C., & Pidgeon, N. (2019). Deliberating the social acceptability of energy storage in the UK. *ENERGY POLICY*, 133, 110908. <https://doi.org/10.1016/j.enpol.2019.110908>
- Utsi, E. C. (2017). *Ground Penetrating Radar: Theory and Practice*. Butterworth-Heinemann.
- Van Essen Instruments B.V. (2024). *TD-Diver*. <https://www.vanessen.com/products/data-loggers/td-diver/>
- Venkatesh, J., Partheeban, P., Baskaran, A., Krishnan, D., & Sridhar, M. (2024). Wireless sensor network technology and geospatial technology for groundwater quality monitoring. *Journal of Industrial Information Integration*, 38, 100569. <https://doi.org/10.1016/j.jii.2024.100569>
- Vidal, R., Olivella, S., Saaltink, M. W., & Diaz-Maurin, F. (2022). Heat storage efficiency, ground surface uplift and thermo-hydro-mechanical phenomena for high-temperature aquifer thermal energy storage. *GEOTHERMAL ENERGY*, 10(1), 23. <https://doi.org/10.1186/s40517-022-00233-3>
- XT-DTS Hardware Manual*. (2016). Silixa Ltd.
- Yang, Z., Deng, Y., Qian, J., Ding, R., & Ma, L. (2021). Characterizing temporal behavior of a thermal tracer in porous media by time-lapse electrical resistivity measurements. *HYDROGEOLOGY JOURNAL*, 29(3), 1173–1188. <https://doi.org/10.1007/s10040-021-02307-1>
- Zhang, B., Gu, K., Bayer, P., Shi, B., Xiang, F., Wei, Z., & Wang, B. (2021). *Estimation of subsurface flow from high-resolution temperature profiles*. <https://www.authorea.com/doi/full/10.22541/au.163429102.21164496/v1?commit=219b8ff153f7517674f1f7919f99f2e6a5d9f0d3>





Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Project funded by

 Schweizerische Eidgenossenschaft  
Confédération suisse  
Confederazione Svizzera  
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs,  
Education and Research EAER  
State Secretariat for Education,  
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