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CATALOGUE OF VULNERABLE AQUIFERS FOR DROUGHT V.1

Version: v1

Project	101075609 — GSEU — HORIZON-CL5-2021-D3-02	
Deliverable Data		
Deliverable number:	**D4.3**	
Dissemination level:	**Public**	
Deliverable type:	**Report**	
Work package:	**WP4 – Appraisal, Protection and Sustainable Use of Europe's Groundwater Resources**	
Lead WP/Deliverable beneficiary:	**BGR**	
Deliverable status		
Verified (WP leader):	**Peter van der Keur (GEUS)**	
Approved (Coordinator):	**Julie Hollis (EGS)**	
Author(s):		Affiliation:
Bentje Brauns, John P. Bloomfield, Joel A. Blackburn		UKRI-BGS
David Pulido, Antonio Juan Collados-Lara, Leticia Baena, J. de Dios Gómez and Juan Grima-Olmedo		IGME
Stefan Broda		BGR

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Revision History		
Author(s):	**Description:**	**Date:**
Task 4.1 group	Draft deliverable	19/12/2024
Pascal Audigane (BRGM)	Revision 1	07/01/2025
Bentje Brauns (BGS)	2nd Draft	13/01/2025
Francesco Pizzocolo	Final version	14/01/2025

Executive Summary

Groundwater resources serve as strategic assets for water supply during periods of limited surface water availability, especially under drought conditions. These resources, however, must be utilized sustainably to ensure that their use remains within environmental limits and does not compromise the resilience of the groundwater systems. This deliverable contributes to the broader objective of raising awareness about the critical importance of groundwater aquifers. It focuses on identifying aquifers with high resilience—those capable of recovering from extreme conditions—that can serve as strategic resources during droughts, as well as those with low resilience that require heightened protection.

This document, Deliverable 4.3, details the methodological approaches designed to study the dynamics of groundwater systems, particularly in the context of droughts. The primary output is the development of a framework to generate a catalogue of aquifers classified by their vulnerability and resilience to drought. This catalogue is intended to serve as a decision-making tool for policymakers, stakeholders, and water resource managers, providing essential insights into sustainable groundwater management practices.

Objectives and Methodologies

The deliverable outlines a comprehensive strategy to:

1. **Identify and Characterize Groundwater Droughts:**
   - Conduct a detailed analysis of historical groundwater levels and trends to identify episodes of drought
   - Utilize a range of standardized indices such as the Standardized Groundwater Level Index (SGI) to ensure consistency and comparability across European regions.
2. **Quantify Groundwater Level Trends:**
   - Detect and analyse temporal trends in groundwater levels
   - Employ advanced statistical and geospatial techniques to understand long-term changes and autocorrelation structures within groundwater datasets.
3. **Evaluate Performance Indicators of Resilience and Vulnerability:**
   - Develop and apply metrics to assess the resilience of aquifers to drought conditions
   - Identify aquifers at high risk of over-exploitation and environmental degradation.
4. **Recommend Workflows for Analysis and Decision-Making:**
   - Propose high-level and detailed workflows for drought characterization, trend detection, and performance indicator analysis
   - Facilitate the integration of findings into actionable policy frameworks.

Data and Sources

This deliverable's methodologies are informed by an extensive review of existing literature, data collected through European Geological Surveys, and inputs from various institutional questionnaires. This approach ensures that the proposed methodologies address the diverse needs and conditions across Europe. The insights gathered inform a robust and scalable approach suitable for application at both national and European levels.

Key Outcomes and Future Directions

The outcomes of this deliverable include:

- A clear description of methodologies to be applied in identifying and categorizing aquifers based on their vulnerability and resilience
- Recommendations for workflows that standardize the process of groundwater drought analysis, ensuring consistency across regions
- A roadmap for the integration of findings into the European Geological Data Infrastructure (EGDI), enabling widespread access and utilization of the catalogue of aquifers
- This deliverable is part of a broader initiative. While the current report focuses on methodological development, a subsequent deliverable (D4.4) will apply these methodologies to a comprehensive European dataset collected through the European Groundwater Monitoring Database (EUGM). The results will enrich the catalogue and support the ongoing implementation of sustainable groundwater management strategies.

Broader Implications

Groundwater systems are often overlooked in traditional water resource management. This deliverable, aligned with the 2022 United Nations World Water Development Report's call to "make the invisible visible," underscores the necessity of integrating groundwater considerations into policy and planning. By identifying aquifers with strategic importance and those requiring protection, this work contributes to the resilience of Europe's water systems against the growing threats posed by climate change and increasing water demands.
This extended summary reflects the strategic vision and technical rigor underpinning the efforts to safeguard groundwater resources for future generations. It emphasizes not only the scientific advancements made but also the actionable insights provided for decision-makers across Europe.

Abbreviations	
EC	**European Commission**
EGDI	European Geological Data Infrastructure
EGS	European Geological Surveys
EU	European Union
EU	European Union
EUGM	European Groundwater Monitoring Database
GRACE	Gravity Recovery and Climate Experiment
GSEU	Geological Service for Europe
GTAM	Groundwater Trend Analysis Method
H2020	Horizon 2020
ITA	Innovative Trend Analysis
JRC	Joint Research Centre
NAO	North Atlantic Oscillation
PDSI	Palmer Drought Severity Index
RDI	Reconnaissance Drought Index
SDI	Streamflow Drought Index
SGI	Standardised Groundwater level Index
SPEI	Standardised Precipitation-Evapotranspiration Index
SPI	Standardised Precipitation Index
SRI	Surface Runoff Index
SSRI	Subsurface Runoff Index
TWS(A)	Terrestrial Water Storage (Anomaly)
WFD	Water Framework Directive
WP	Work Package

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1. Introduction

The target of this deliverable is to describe the methodological approach that will be applied to study the dynamic of groundwater status and generate a catalogue of vulnerable and resilient aquifers for droughts. It will allow to identify those with lower vulnerability and higher resilience, which might be strategic resources to face droughts, and those that should be protected due to their higher vulnerability and lower resilience.

There will be two sections for this deliverable. This first section (this report, D4.3)) will review and discuss the concepts and methodologies that will need to be used to produce a catalogue of aquifers vulnerable to drought and the second report (D4.4) will present the results of the data base analysis using the methods proposed in this report.

In this section we will:

- Review and describe methods for quantifying groundwater drought in Europe based on analysis of historic groundwater heads / levels
- Review and describe methods for the quantification of trends and autocorrelation and cross-correlation structures in groundwater level time series
- Review and describe methods to quantify groundwater drought vulnerability and resilience. This will draw on different simple indices, and concepts and information related to the management and/or quantification of groundwater droughts and correlation structures in groundwater level time series
- Give recommendation for workflow for drought characterisation and trend analysis (Section 5) and analyses of groundwater performance indicators.

1.1. Definitions

In this section an overview is provided of definitions for the terms: drought, groundwater drought, groundwater vulnerability and resilience, and, by extension, groundwater vulnerability and resilience to drought.

1.1.1. Drought

In the literature we can find many different definitions of droughts (e.g. Lloyd-Hughes, 2014). A very simple one introduces drought as a water deficit in relation to the long term mean conditions (Sheffield et al. 2011). We will follow this by defining drought as some water related quantity having a lower value than normal. This quantity can be e.g. precipitation or precipitation minus evaporation (meteorological drought), soil moisture (agricultural drought), streamflow (hydrological drought), or groundwater head (groundwater drought).

We will not connect cause-effect relationships to various types of droughts as is sometimes suggested for different types of droughts: meteorological, hydrological, agricultural, and socioeconomic or operational drought (e.g. Mishra and Singh, 2010; Hidalgo-Hidalgo et al., 2022). We will also stay away from the term “socio-economic or operational droughts” (Lines et al., 2018). This is more about water scarcity that may arise from droughts. Water scarcity or shortage relates to water availability and water demand. Therefore, it also depends on the anthropogenic activities and management (Mishra and Singh, 2010; Hao and Singh, 2015).

1.1.2. Groundwater Drought

Groundwater drought is an episodic natural hazard that impacts Europe over a wide range of spatio-temporal scales, both directly and indirectly. For example, it impacts people through the adverse effects on water supplies, food production, industry, and recreation, as well as adverse environmental impacts, including changes in ecosystem structure and function. A catalogue of some of these impacts of groundwater drought across Europe has previously been developed by Stahl and co-workers (e.g., Stahl et al., 2016).

Given that groundwater droughts can deviate from driving meteorological droughts with important consequence for their impacts (Van Loon, 2015, Van Lanen et al., 2016) it is useful to define and briefly characterise groundwater droughts in relation to the general concept of droughts.

Droughts have been conceptualised as affecting different components of the water cycle, e.g. meteorological drought and hydrological drought, the latter including groundwater drought (Mishra and Singh, 2010), or by their impact on different compartments of the environment or society, e.g. ecological drought (Slette et al., 2019) or agricultural drought (Orimoloye, 2022).

Groundwater drought is usually conceptualised as a type of hydrological drought (Van Loon, 2015), where, citing Tallaksen and Van Lanen (2004), Van Loon (2015) defined hydrological drought as:
"a lack of water in the hydrological system, manifesting itself in abnormally low streamflow in rivers and abnormally low levels in lakes, reservoirs, and groundwater".

An important element of this definition is that hydrological drought, including groundwater drought, is a relative, not absolute concept, i.e. groundwater drought is defined as a "lack of water" compared to some reference state, or as an "abnormally low level" of groundwater compared to some measure of normal (Chang and Teoh, 1995, Eltahir and Yeh, 1999).

Some works have suggested that droughts may also be a linked hydro-meteorological-social construct (Lange et al., 2017) or that they should be framed by large-scale, long-term environmental changes such as those associated with the Anthropocene (Van Loon et al., 2016). Both of these concepts are out of scope for this project and the focus in this report is on groundwater droughts in the observational record and in the context of groundwater level forecasts.

Groundwater droughts can express themselves as decreased groundwater recharge, suppressed groundwater levels and reduced groundwater discharge, which for meteorological drought occur in this order. Consequently, some researchers have defined sub-types of groundwater drought in terms of groundwater recharge droughts, groundwater storage droughts, and groundwater discharge droughts also referred to as baseflow droughts (Hellwig and Stahl, 2018, Hellwig et al., 2021). Peters and co-workers developed this concept of propagation of meteorological drought in the early 2000s when simulating the hydrology of an idealised Chalk catchment (Peters and Van Lanen, 2003, Peters et al., 2005) and applied this conceptualisation to the Pang catchment, Berkshire (Peters et al., 2006). These definitions of sub-types of groundwater are occasionally used in the peer-reviewed literature. For example, Barthel et al. (2021) identified the importance of understanding recharge in the context of the typically small, low storage groundwater systems in Sweden and highlighted the challenge that groundwater drought recharge studies are typically site specific and that transferability of findings from one setting to another is challenging. Wossenyeleh et al. (2022) investigated groundwater recharge droughts in the context of wider drought propagation process in semi-arid regions of Ethiopia. The concept of a groundwater discharge drought has been particularly useful to those working on karst systems with major spring outflows. For example, Fiorillo and Guadagno (2012), and Fiorillo and Guadagno (2010) defined groundwater drought in a karst system in southern Italy based on low flows in spring discharge time series.

Most studies of groundwater drought have focussed on droughts as defined by abnormally low groundwater levels (heads), or some standardised value of levels or heads (Bloomfield and Marchant, 2013), in unconfined or confined aquifers (Mishra and Singh, 2010). An additional benefit of characterising groundwater drought based on changes in groundwater level is that these data are typically readily available for most groundwater systems. For simplicity, throughout the rest of this report ‘groundwater drought’ is taken to refer to droughts defined by groundwater heads in aquifers unless otherwise stated.

1.1.3. Groundwater Vulnerability and Resilience

Groundwater vulnerability is a term, which has been extensively used with respect to potential deterioration of groundwater resources due to pollution coming from the surface. Different approaches and techniques (Machiwal et al., 2018) have been applied to assess vulnerability, distinguishing intrinsic and specific vulnerability. The Intrinsic vulnerability assesses the risk that a pollutant at the surface reaches the aquifer being pumped (Krogulec et al., 2013). The specific vulnerability expresses this risk for specific contaminants, considering their properties and the potential processes may influence the transport to the aquifer (Gogu et al., 2000). Groundwater vulnerability to pollution depends on intrinsic susceptibility, which depends on aquifer hydrogeological properties, the associated sources of water, the distribution and types of contamination sources (natural and/or anthropogenic), and the contaminant transport (Focazio et al., 2002). The most commonly employed methods to assess vulnerability are the index-based approaches (Taghavi et al., 2022) that include commonly used and much amended methods such as DRASTIC (Aller et al., 1987), SINTACS (Civita and Maio, 2004) or COP (Vías et al., 2006). An opposite concept is defined by the term groundwater resilience, which has been extensively used for both quantitative and qualitative status (Baena-Ruiz et al., 2018). In the literature there are different definitions of system resilience, as, for example, the capacity to return to satisfactory conditions from failure (Louck 1997), or how quickly it recovers from failure (Neves 2014).

In this deliverable we focus on the quantitative status, in which the terms groundwater vulnerability and resilience have been applied to study potential aquifer deterioration or recovery, respectively. For example, the term resilience has been linked to different approaches of the variable mean residence time when analysing aquifer sensitivity to temporal increase of pumping, which takes place during drought periods (Pulido-Velazquez et al., 2020). A preliminary simple approach of the mean residence time can be obtained as the total aquifer storage (S) divided by the average recharge (R). This simple approach has also been used to assess groundwater vulnerability with respect to potential pollution and quantitative status (Baena-Ruiz et al., 2021). Intuitively, aquifers in which the recharge value is close to the storage are extremely vulnerable to temporal increase of pumping, even in periods when pumping is smaller than the average recharge. In cases with very low recharge, other authors propose to use other simple index, defined as the aquifer storage (S) divided by total groundwater extractions (P) to assess vulnerability to pumping (Schoonderwoerd et al., 2021). Molina et al. (2012) define a sustainable aquifer yield indicator as the relation between the residence time (relation between aquifer storage S and Recharge R: S/R), and the relation between the aquifer Pumping P and the so-called aquifer Social Yield Y, which is the maximum abstraction given environmental flow needs. The indicator is defined by this formula: (S/R)/(P/Y). For Y equal to the average recharge R, this gives the S/P index (Schoonderwoerd et al. 2021).

1.1.4. Groundwater Vulnerability and Resilience to Droughts

The general concept of vulnerability to drought has been studied in the scientific literature for different sectors (and various types of water resources). The European Joint Research Centre (JRC) published a report (Meza et al., 2019) that summarizes the results of a global survey for agricultural systems and domestic water supply in which experts on hydrology and water resources management are included. They identify different indicators/variables (social, economic, infrastructure, crime and conflict, environmental and farming practices) which are grouped into subcategories: social susceptibility, environmental susceptibility, lack of coping capacity (short-term capacity of adaptation) and lack of adaptive capacity (long-term horizon of capacity of adaptation). In the 71 selected indicators, only 5 of them make a direct reference to water resources (population without access to clean water; poor water quality; total dam capacity; retained renewable water, and water stress), but none of them mention the groundwater directly, the terms aquifer and groundwater are not even mentioned in the report. In the scientific literature we find a small number of papers about groundwater and vulnerability to droughts (Richts and Jaroslav, 2016). The drought vulnerability of Richts and Jaroslav (2016) is focused on emergency supply of safe drinking water during hydroclimatic disasters. The amount of abstraction is so small that sustainability is not considered as an issue. The requirement of safe drinking water thus leads to a preference for confined aquifers with little or no replenishment. This is not suitable for regular drought mitigation.

We define groundwater vulnerability to droughts as a measure of the probability that drought leads to changes of groundwater quantity that have negative impacts on nature and/or society. So, groundwater vulnerability to drought is a concept related to groundwater drought dynamics. It is also a relative concept: it measures the impact at one site to impact at another site.

Based on this definition, the autocorrelation of the groundwater head time series is the key characteristic (cf. Wendt et al 2020). It is unlikely that the existence of (downward) groundwater quantity trends is a useful primary indicator of groundwater vulnerability to drought. However, they may be useful to validate an indicator, as it is expected that occurrence of drought in a vulnerable area leads to more negative trends than in less vulnerable areas. We need to understand over what timescales, and these would need to be estimated possibly depending on the drought dynamics.

A complication in the assessment of groundwater vulnerability to drought is the variety in impacts (depending on the duration) and the mixed natural and anthropogenic character of groundwater drought. Impacts include environmental damage (when heads drop too low, so groundwater no longer reaches the rootzone for groundwater dependent vegetation or baseflow discharge dropping below environmental limits), increase of greenhouse gas emission (when the groundwater table drops in carbon rich soils), limitations for groundwater use (wells drying up, increased pumping energy requirements for wells), and damage to buildings and infrastructure due to land subsidence.

Because the duration plays a role in the impacts, not only the formation of groundwater drought but also the recovery is important (van Loon et al., 2024). In the analyses of groundwater drought, the concept of resilience has also been applied. Assuming that we have a failure for a specific level of drought or threshold of standardized groundwater indices, the resilience is defined as the capacity to return to satisfactory conditions from failure (Louck 1997), or how quickly it recovers from failure (Neves, 2014). In fact, different index-based approaches can be used to perform an assessment of the resilience and other concepts related to groundwater performance to manage drought (Neves, 2024; Pulido-Velazquez et al., 2020).

1.2. Scope of this Document

Groundwater resources can be used as strategic resources for water supply during times that little surface water is available. However, this can only be done in a sustainable way if the total water use stays within environmental limits and if the resilience of the groundwater system is large enough to enable this supply without damage. This requires integrated (and adaptive) water management. Unfortunately, the subsurface part often does not receive proper attention in water management. The 2022 edition of the United Nations World Water Development Report addressed this lack of attention and was titled “Groundwater: Making the invisible visible”, which highlights the necessity to raise awareness about the essential role of groundwater resources for a sustainable development. In the current report we aim to contribute to raise awareness of the significance of groundwater aquifers, and to identify those with high resilience (capacity of a system to recover from extreme conditions) that can be strategic to face drought, and those with low resilience that should be protected.

In this deliverable we study the dynamics of groundwater status (droughts and trends) and assess different groundwater performance indicators relevant to drought management, including groundwater resources vulnerability and resilience (Neves, 2024). The “catalogue of vulnerable aquifers” will be implemented on the European Geological Data Infrastructure (EGDI) platform.

Different approaches will be applied to assess groundwater resilience to drought at head observation points (Neves, 2024) and groundwater body scale (Pulido-Velazquez et al., 2020). There are different aspects that should be considered to study groundwater resilience to drought, and there is not a clear consensus in the scientific approach to be applied. We propose to collect evidence from different approaches to arrive at more robust conclusions. Finally, the robustness of the groundwater resilience to drought will be analysed by exploring agreements between the different assessments.

2. Groundwater Drought Identification and Characterisation

2.1. Literature Review of Drought Analysis Approaches Used in Europe

A literature review has been carried out in May 2024on the Web of Science using the topic “groundwater” AND “Europe” AND “analysis” AND “drought”, returning 46 results, of which 37 were relevant (listed in Annex 1). No date limits were set for the literature search, but most results were from recent years, which is reflective of the increase in larger-scale drought analysis and increased research on droughts under the growing pressures of climate change and increasing demand on resources. A small amount of additional literature found via other online searches was also included. The relevant references were then reviewed and filtered for method-related articles. This section summarises the methods used to analyse groundwater droughts. A number of these papers analyse meteorological and hydrological droughts with groundwater drought analysis forming part of the study scope. A significant number of the literature results returned did not have a European-wide focus, but focus on a region, country and occasionally on a local scale instead. A range of observation and simulation methods are used, with most-European wide studies using models and/or GRACE derived total water storage (anomaly), TWS(A), to simulate and analyse past droughts, whereas national-local studies more commonly use observational groundwater level data.

Many analysis methods used in literature look to standardise spatially variable observational data. The majority of the methods include Standardised Groundwater level Index (SGI), Standardised Precipitation Index (SPI) and the Standardised Precipitation-Evapotranspiration Index (SPEI); occasionally in combination with the Reconnaissance Drought Index (RDI), Surface Runoff Index (SRI), Streamflow Drought Index (SDI) and Subsurface Runoff Index (SSRI). Methods such as the SPI and SPEI are meant for meteorological droughts but are sometimes used to gauge hydrological and hydrogeological droughts (e.g., Bresinsky et al., 2023). Kubicz (2018) stated that in order to apply SPI to hydrological and hydrogeological drought, the significance and level of correlation between drought indices in the area should be assessed.

Brlekovic and Tadic (2022) suggested that the correlation between SPI and SGI is sensitive to catchment characteristics, even in small catchments. Authors who used multiple standardised drought indices including SGI often looked at a range of timescales 1-48 months and commonly found that the groundwater droughts took longer to set on than surface water droughts but often lasted longer. Kubicz (2018) found that two-year meteorological droughts (SPI-24) had the strongest influence on groundwater deficits at a site in Northern Poland. Kubicz and Bak (2019) found (from another study in Poland) that there was not a linear relationship between precipitation droughts and hydrogeological droughts, suggesting that groundwater droughts are affected by other factors independent of rainfall (e.g. unsaturated zone properties, and anthropogenic factors). Brlekovic and Tadic (2022) found that the correlation between SPI and SGI varied at different timescales but was closest at the 48-months scale (for a small lowland catchment in Croatia). Using SRI and SGI, Sutanto et al. (2020b) found that hydrological drought forecasts outperformed meteorological (SPI) drought forecasts over the pan-European region, even showing predictive power. Sutanto and Van Lanen (2022) show that catchment memory (using base-flow index) explains hydrological drought forecast performance, and that rivers with large memory yield better drought prediction. Sutanto et al. (2020a) also found that dynamical forecasts derived from seasonal forecasts showed higher predictability. Minea et al. (2022) using SPI, SPEI, SDI & SGI to analyse droughts in Eastern Europe found that Bravais-Pearson correlations showed a close connection between meteorological and hydrological droughts and a close connection between hydrological and groundwater drought at shallow groundwater depths (<5 m). The Palmer drought severity index (PDSI) (Palmer, 1965) is another method used for characterising (meteorological) droughts. It focusses on the amount of precipitation required for the near-normal operation of the established economy of an area (Palmer, 1965) and is more suited for impact of meteorological drought on agricultural than on hydrology (Mishra and Singh, 2010).

Groundwater drought is not only due to propagation of meteorological drought. In the past decades the influence of anthropogenic activities on groundwater has been larger than climate change (e.g. Peters et al., 2006, Wanders & Wada, 2015, Zhang et al., 2018). Kunwar et al. (2024) attributed groundwater depletion in India to population growth, rapid urbanization, proliferation of factories and the expansion of agriculture. Riedel and Weber (2020) found that land use and land use change have had a large influence on recharge and that the impact of climate change for the future is uncertain.
Rusli et al. (2024) reported that the anthropogenic impact is larger than impact of climate change for the Bandung aquifer up to 2100. Because of this uncertainty of the causes of groundwater drought we focus on the observational records of groundwater itself.

The density of groundwater monitoring wells in combination with the spatial variability of groundwater levels and groundwater droughts is limited. This may be a reason that, most European-wide groundwater drought studies used GRACE derived terrestrial water storage (e.g., Van Loon et al., 2017, Cammalleri et al., 2019, Gerdener et al., 2023, Güntner et al., 2023). The spatial resolution of these results is much coarser than for groundwater monitoring wells, so that the variability is reduced. The latest dataset is GLWS2.0 which is derived via assimilating maps of GRACE/-FO TWSA into a hydrological model (Gerdener et al., 2023). GLWS2.0 shows many similarities with other global land surface models such as the catchment land surface model, although it exhibits somewhat lower trends and lower annual amplitudes (Gerdener et al., 2023). GLWS2.0 enables drought and flood events to be observed in more detail though such events are not well resolved spatially with GRACE/-FO (Gerdener et al., 2023). Problems encountered when using TWS include failing to capture spatially variable drought patterns probably due to the coarse resolution (Van Loon et al., 2017); and negative TWS trends due to groundwater exploitation rather than from natural droughts (Liu et al., 2020). There are also uncertainties associated with observed TWS changes these having been studied for regions such as river basins by Boergens et al. (2022). Cammalleri et al. (2019) analysed the relationship between SPI and GRACE for drought monitoring. They found that there were good correlations between TWSA and long-term SPI (12-48 months) and that the SPI-12 provided a good proxy of long-term hydrological drought over Europe, but not at the global scale.

Subsurface water storage in Europe has been assessed through other models such as fully coupled terrestrial models (e.g., Hartick et al., 2021). Other innovative methods for analysing groundwater droughts in Europe include the use of AI-based methods for processing monitoring data. Ma et al. (2022) combined long short-term memory networks (LSTM) and transfer learning to produce water table depth anomaly estimates at the European scale from meteorological information at locations without any sufficient groundwater data. The agreement with in-situ water table depth measurements from 2569 wells showed a Pearson correlation coefficient $\geqslant$ 0.5, root-mean-square error $\leqslant$1.0 and Kling-Gupta efficiency $\geqslant$0.3 at about half of the pixels. However, they performed poorly in deep aquifers, perhaps due to the inability to capture very long-term dependencies between water table depth anomalies and hydrometeorological variables (Ma et al., 2022).

Other groundwater drought analysis methods used long-term time series data, distinguishing groundwater droughts using various thresholds. Gurwin (2014) mentions the annual minimum approach level (time series divided in annual periods and for each annual period the minimum is selected, but this means droughts have no duration and cannot be multi-year) and threshold approach levels (drought derived from threshold exceedance probabilities). During a study in Poland, Gurwin (2014) defined groundwater droughts by establishing periods when the negative deviation of the moving average during the period of analysis exceeded 50% of the standard deviation and used GIS spatial modelling to classify drought vulnerability. Gurwin (2014) stipulates that these threshold values need to be regularly assessed (every 5 years) and altered accordingly, and that there is not a clearly defined boundary between different drought levels or when an emergency is declared.

European droughts are commonly defined by reaching certain thresholds against long-term water level data; however, little is known about whether or not/ to what extent climatic oscillations influence groundwater levels (climatic teleconnection signals). Rust et al. (2018) developed a conceptual model of the importance of teleconnection signals through the aquifer system in Europe (i.e., from precipitation and evapotranspiration to groundwater discharge). They found key spatial and temporal signals between climatic oscillations, precipitation, groundwater recharge and groundwater discharge, with generally positive correlations found between the Northern Atlantic Oscillation (NAO) and precipitation in northern Europe indicating a strong control on water availability for groundwater recharge (Rust et al., 2018).

The drought assessment methods using (standardized) indices or threshold level assume stationarity of the (groundwater) variation in time. In many areas around the world, the stationarity is violated due to anthropogenic influences and climate change (e.g. Chan et al., 2021). Some efforts have been made to account for non-stationarity in drought indices (e.g. Wanders et al., 2015, Laimighofer & Laaha, 2022, Jehanzaib et al., 2021, Rigby & Stasinopoulos 2005).

2.2. Review of drought analysis approaches used by national and state surveys and institutional needs related to groundwater drought identification and characterisation

The participating national and state geological surveys within this project were invited to provide a concise description of their respective institutional interests and needs related to groundwater drought identification and characterisation, and, if already being conducted, the approaches being employed by each partner.

The following questions were provided as prompts or guides to provide some structure to the responses:

- What is your definition of drought?
- Do you have a major drought in your area that you use as ‘benchmark drought’ (and if yes, in which year)?
- Are you currently interested in or undertaking national or sub-national drought analysis?
- What time scales are of interest to you?
- What spatial aggregation do you use?
- Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
- If you are already undertaking drought analysis, what methods are currently in use?

- Have you encountered any analysis-related challenges?
- Are there additional methods you plan to use or would like to explore in the future?
- What are your ideas about the GSEU groundwater drought analysis for Europe?

2.2.1. Results

What is your definition of drought?

88% of the national and state geological surveys that provided feedback responded citing a range of definitions of drought and groundwater droughts, including two of them indicating that there was no common definition and/or that definitions were based on the specific objectives and needs of each project.

Three (14%) of the respondents indicated that drought was primarily defined based on observed impacts, and another respondent (Sweden) indicated that a mix of a measure of the relative groundwater level (in percentile) in combination with impact-related factors, such as dependency on groundwater and previous experiences of impacts from low levels, are used as combined approach to define groundwater drought. Overall, a clear majority of responses (71%) reported drought definitions based on relative concepts, with a variety of indices and approaches used to indicate drought status.
A number used some form of SPI as defined by the World Bank to define meteorological drought and the related SPEI (Vicente-Serrano et al., 2010), which is based on the difference between the amount of precipitation and evapotranspiration, to define meteorological droughts (e.g. Croatia).

Groundwater droughts are typically defined as below-normal groundwater levels at an observation borehole over a specified period (seasonal to interannual) (e.g. France). However, there are caveats to this. For example, it has been noted by the Dutch survey that "a challenge in the application of this definition is the fact that normal is shifting e.g. due to the increasing variability of potential groundwater recharge (precipitation minus reference evaporation)". In addition, the Polish survey note that "we speak of drought only when the scale of the phenomenon is greater than the local one, and its genesis is natural (or mainly natural)". The Slovenian survey does not formally report on groundwater drought but notes that their national Environment Agency "use[s] the groundwater drought indicator in intergranular aquifers based on the assessment of the intensity and spatial distribution of the monthly standardized groundwater level index (SGI) for individual years". The British Geological Survey (UK) uses the SGI to investigate and characterise site- to national-scale groundwater drought status.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?

Of 17 respondents to this specific question, 71% of the responding surveys reported having one or more years considered as national or regional 'benchmark droughts'. Table 1 summarises the years (or periods) identified as benchmark droughts with particularly extreme years emphasised in bold. The table shows a wide range of national perspectives on what constitutes a benchmark drought in the different states. However, there are a couple of periods, for example 1975-76 and 2018, that have been commonly identified as being particularly severe suggesting that these periods may be associated with supra-national, widespread European drought.

Table 1: Summary of droughts identified by surveys as "benchmark droughts". Bold numbers indicated years that have been highlighted as the most significant drought by the respondent.

Respondent	Benchmark droughts
Austria	2003; 2018
Belgium (VMM)	1921; 1959; **1976**; 2018; 2020
Denmark	1899; 1947; 1959; 1976; 1992; **1995-97**; 2018
Estonia	1992-94; 1996-97; 2002-04; 2005-07
Germany	**2003**; 2018; 2019
Greece	1989-90
Ireland	**1765-68**; 1887; 1938; 2018
Malta	1961; 2024
The Netherlands	1911; 1921; 1959; **1976**; 2003; 2018
Poland	1990-92; 2015
Romania	2000; **2011**; 2018; 2019; 2022
Serbia	2000; 2007; 2012; 2017; 2021
Spain (IGME)	1991-95; 2016-17;2021-24
UK	**1975-76**; 1988-93; 1995-98; 2004-2006; 2010-12

Are you currently interested in or undertaking national or sub-national drought analysis?

96% of the respondents stated that they were either undertaking or were interested in drought analysis at the national- or sub-national scales. Most of those responding positively to this question were currently actively undertaking some form of national- or sub-national-scale drought analysis or were developing this capability (15 state surveys) with an additional 8 state surveys interested in developing some capabilities related to drought analysis (Table 2).

Table 2: Level of activity/interest in national or sub-national drought analysis by respondent.

Respondent	Currently active	Developing capability	No current capability but interested	Other agency responsible
Austria	x			
Belgium (VMM)	x			
Croatia			x	
Cyprus			x	
Czechia		X		
Denmark	x			
Estonia		X		
Finland			x	x
France	x			
Germany	x			x
Greece			x	
Hungary	x			
Ireland		X		
Italy			x	
Malta			x	
The Netherlands	x			
Poland	x			
Romania			x	
Serbia	x			
Slovakia	x			
Slovenia				x
Spain (IGME)			x	
Sweden	x			
UK	x			
Total	12	3	8	3

What time scales are of interest? What spatial aggregation do you use?

These scales of interest and level of spatial aggregation were presented as two separate items in the questionnaire, but the results are reviewed here together as they are closely related items.

Slightly more partners responded with information about timescales of interests than with information about spatial scales over which drought information was aggregated (Table 3). Of those surveys that responded related to the timescale of interest for their drought analysis requirements there was a broadly equal interest in drought dynamics from monthly to multi-annual scales. Similarly, for those that responded with information about the area over which drought analysis is aggregated there was broadly equal interest over the site / borehole to national scales. However, it should be noted that there was a specific interest in aggregation at the groundwater body scale and all surveys with the exception of the one from the UK (who have no longer responsibility of reporting against the EU Water Framework and Groundwater Directives) highlighted this scale of interest.

Table 3: Summary of timescales of interest and aggregation scales by respondent.

Respondent	Timescale			Aggregation scale			
	Monthly	**Annual**	**Multi-annual**	**Site / borehole**	**Body**	**Regional**	**National**
Austria							
Belgium (VMM)	x	x		x	x	x	
Croatia							
Cyprus		x	x		x		
Czechia	x	x	x		x		
Denmark	x	x	x	x	x	x	x
Estonia	x	x	x	x	x	x	x
Finland							
France	x	x	x	x	x		
Germany	x	x	x	x	x	x	x
Greece	x	x	x			x	
Hungary							
Ireland	x	x	x				
Italy							
Malta		x					x
The Netherlands	x	x	x	x			x
Poland	x		x	x	x	x	x
Romania							
Serbia	x	x	x			x	
Slovakia							
Slovenia	x	x		x	x		
Spain (IGME)					x	x	x
Sweden	x	x		x			
UK	x	x	x	x		x	x
Total	**14**	**15**	**12**	**10**	**10**	**9**	**8**

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?

Just under 71% of the 17 surveys who responded specifically to this question said that they considered the effect of autocorrelation in the groundwater level time series when analysing groundwater drought with another 18% indicating that they should be using autocorrelation methods to better understand memory in groundwater systems, particularly under drought conditions.

It is clear that different Surveys use a range of methods with slightly different aims and purposes. For example:

- The Danish survey is "currently investigating temporal lags between the hydrological indices based on precipitation, soil moisture, streamflow from upper groundwater and deeper groundwater"
- The Estonian survey has "examined autocorrelations in groundwater levels through various small-scale and nationwide projects. However, they have not yet conducted a detailed analysis regarding lags in droughts"
- The French survey is "looking for autocorrelation in groundwater levels and propagation/lags in droughts, including how these parameters depend on low-frequency [driving climate] variabilities"
- The Irish survey has "used autocorrelation as a proxy for groundwater memory to indicate drought susceptibility"
- The Dutch survey has investigated autocorrelation "through transfer-noise modelling of groundwater head time series with precipitation and reference evaporation as explaining variables"
- The Polish survey has produced predictions of groundwater levels "based on autocorrelation (exponential alignment).
- The Serbian survey has characterised "temporal lags, taking into account precipitation, temperature, groundwater, and surface water of an area"
- The Spanish survey (IGME) has investigated "the propagation and lags in droughts [to help assess] the impact of climate change scenarios on droughts and their propagation in an arid Mediterranean basin. A useful approach for planning adaptation strategies"
- The British Geological Survey (UK) understand the relationship of groundwater systems to the "driving climatology and the effect of aquifer and catchment characteristics on system memory and response to meteorological droughts".

Do you consider droughts in multi-aquifer systems and, if so, how?

About 58% of the responding state surveys commented on this question and only Cyprus, Czechia, Denmark, France, the Netherlands and Poland confirmed that they currently consider droughts in multi-aquifer systems. This probably reflects, at least to some extent, the relative sensitivity of the uppermost, typically unconfined, aquifers to driving meteorological droughts. In this context, the UK noted "some limited work on semi-confined / confined aquifer response to drought but generally most UK aquifers are unconfined".

The Polish survey noted that they have been investigating "low levels [heads] at different water bearing horizons" where they "have divided our observation points into groups depending on the depth to the aquifer top. Currently, we do such analyses sporadically, not cyclically".

If you are already undertaking drought analysis, what methods are currently in use?

75% of the responding state surveys described some form of drought analysis that they undertook. As expected, the approaches are quite diverse and are a function of the different organisational needs and priorities. To try and identify commonalities in the approaches adopted, these are summarised in the table below under the heading's descriptive statistics, analysis of SPI/SPEI, analysis of SGI, and modelled forecasts. Note that just because a state survey is not recorded as using any of the approaches does not mean that they are not, it just means that it's not been reported in response in the questionnaire.

As can be seen in Table 4, all four broad approaches have been used, although use of some form of analysis of standardised measure of meteorology (SPI or SPEI) and/or SGI is the most commonly used approach to drought characterisation across the state surveys who responded to the questionnaire. Note however, standardised indices may also be used alongside descriptive statistics and modelling and forecasting techniques.

Table 4: Summary of types of analyses currently in use by respondent.

Respondent	Descriptive statistics	Analysis of SPI / SPEI	Analysis of SGI	Modelled forecasts
Austria		x		
Belgium (VMM)	x	x		x
Croatia				
Cyprus	x			
Czechia	x			
Denmark		x	x	x
Estonia		x	x	
Finland				
France		x	x	
Germany	x			x
Greece				
Hungary				x
Ireland			x	x
Italy				
Malta		x		
The Netherlands			x	
Poland				x
Romania				
Serbia	x	x		
Slovakia	x	x	x	
Slovenia	x		x	
Spain (IGME)		x		
Sweden				
UK	x		x	x
Total	**8**	**9**	**8**	**7**

Each state has a typically distinctive approach. As understanding these approaches is central to planning the approach to be adopted by GSEU we list a state-by-state summary of them here:

- UK: "groundwater droughts are characterised by "model[ling] individual groundwater level hydrographs using Marchant et al. (2022), [by] estimate[ing] SGI time series and extract[ing] droughts for analysis using Bloomfield & Marchant (2013)"

- Spain (IGME): “use the SPI index, and we apply its definition to different variables depending on the type of drought analysed. Using the same mathematical/statistical definition of drought allow us to perform and analyses of the propagation and lags of droughts”

- Slovenia: “method based on ranking statistics defined by lower percentiles indicating low groundwater levels or vice versa. Another method that we have also used in the past is based on the univariate Standardized Groundwater Index – SGI”

- Slovakia: “there is a wide spectrum of methods, attitudes and benchmarks used in Slovakia already summarised in Fendeková and Ženišová (2010). The aim of the monograph is to demonstrate the current state of knowledge of the phenomenon of drought, to propose a methodology for its assessment in the underground component of the hydrosphere and to apply new methodological procedures in the pilot area (Upper Torysa river basin). The book is divided into four main chapters, in which the attention is successively paid to the current state of knowledge of the drought phenomenon (chap. 1), background and methods of hydrogeological drought assessment (chap. 2), a case study of hydrogeological drought assessment in the Upper Torysa catchment (chap. 3) and the impact of hydrogeological drought on water recharge in the Upper Torysa catchment (chap. 4).“

- Serbia: “looks at the correlation between groundwater and drought through groundwater regimes and groundwater balance”

- Poland: “method based on the curves of rising and falling the water table determined from long-term data and determining their probability of occurrence. Due to the provisions of the regulations in force in our country, we wanted to build two extreme forecasting scenarios, which is why we currently use this method”

- The Netherlands: “used the Standardized Groundwater Index and investigated application of this using a variable distribution in time [and that they] are also looking into separating natural (precipitation and evaporation) and anthropogenic (e.g. groundwater pumping) causes of drought”

- Malta: “application of SPI, RDI and drought index (on a national level)”

- Ireland: “have experimented with autocorrelation and “groundwater memory” methods to indicate susceptibility [and] also intend to use SGI and Aquimod to assist in our characterisation and modelling of droughts”

- Hungary: “a multipurpose geo-information system (National Adaptation Geo-information System) [is used to] facilitate the policy-making, strategy-building and decision-making processes related to the impact assessment of climate change and founding necessary adaptation measures in Hungary. In the frame of this project two studies were prepared: ‘Impact of climate change on shallow groundwater’; ‘Vulnerability of drinking water supplying’. The reference interval was 1961–1990 and climate model projections were calculated for 2021–2050 and 2071–2100 periods. [However] detailed analysis of groundwater level time series was not performed”

- Germany: “We have performed groundwater modelling to identify areas where low groundwater levels might happen in the future due to climate change, although this study hasn’t been done specifically for drought analysis. Drought analysis has been mainly done by the local environmental authorities”

- France: “different methodologies are used for undertaking drought analysis. Primarily, we use an indicator (Indicateur Piézométrique Standardisé – IPS) which is very similar to the well-known SGI to determine the state of the water table and describe groundwater drought. Recently, we also developed “drought indicators” for local studies that can be also used on a larger scale such as the discharge speed without water input to illustrate groundwater resistance to rainfall deficit, [an] indicator of groundwater sensitivity to rainfall, [an] indicator based on periodogram or wavelet analysis to determine the system inertia and the response of the water table to meteorological drought, [and an] indicator to characterise the impact of groundwater droughts on surface hydrology. While the IPS is more relevant for characterizing the state of the water table (and drought), these last indicators characterise more the aquifer vulnerability/resilience to drought.

- Estonia: “utilized several indices to calculate the components of drought events. These indices include the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Reconnaissance Drought Index (RDI), Standardized Groundwater level Index (SGI), and Standardized Sub-surface Runoff Index (SSRI). These tools have provided a robust framework for understanding the complex interactions between meteorological, hydrological, and groundwater data during drought events”

- Denmark: “hydrological indices [are estimated] for [a] 30-year simulation using the [national] DK-model”

- Czechia: “identification (visual and partially automated) of various hygrograms of different types of level fluctuations in order to distinguish between the effects of natural dynamics, groundwater withdrawals, measurement errors and other influences and to select representative types of fluctuation. We collect and have at our disposal all the principal driving forces - withdrawals, precipitation, infiltration, evapotranspiration, fluctuations in surface water levels, etc.”

- Cyprus: “groundwater levels, from our telemetric monitoring network, are evaluated yearly and compared manually with that of the previous year(s)”

- Austria: “use the Standardized Precipitation Index (SPI) to characterize meteorological droughts and also the Standardized Precipitation Evapotranspiration Index (SPEI) as a preferred extensions using ET approaches adapted for Austria”.

- Belgium (VMM): “Currently Flanders Environment Agency (VMM) mostly focusses on the phreatic groundwater above the main aquitards in Flanders’ subsoil. For a set of selected phreatic groundwater wells physical (SWAP) or timeseries analysis (pastas) models for the past 30-year periods (or a fixed 30-years reference period) are built (calibration + data assimilation procedures).

- Daily groundwater levels at the monitoring point level are classified in percentile classes with regard to the 30-years reference period: absolute comparison to the whole 30-years period and relative comparison with regard to the same day of the year in the reference period. The distribution of the monitoring wells over the different percentile classes gives an idea about the deviation from normal (absolute or relative) for a certain date, and its evolution. To quantify the deviation from normal we show the distribution of the differences between mean groundwater level per season (or week, month, …) and the mean groundwater level for that season over the reference period."

Have you encountered any analysis-related challenges?

Seventeen of the surveys answered this question and of those 76% reported analysis-related challenges when characterising groundwater droughts. Four reported no challenges. The challenges appear to fall into four broad classes (Table 5), namely:

- Data quality (length of record, frequency and / or regularity of observations)
- Representativeness of observation boreholes of wider groundwater systems of interest
- Accounting for the variability or trends in groundwater levels over a range of time scales (both from natural variability and changes in climate due to anthropogenic climate change)
- Accounting for changes in water resource management practices and particularly abstraction summarises the responses against these four broad categories.

Table 5: Summary of reported analysis-related challenges by respondent.

Respondent	Data quality	Representativeness of observation boreholes	Accounting for natural or Climate Change variability / trends	Accounting for abstraction and water resource management effects
Austria	x			x
Belgium (VMM)	x		x	
Czechia		x		
Denmark				x
Estonia	x			
France			x	
Finland			x	
Germany	x	x		x
Ireland	x			
The Netherlands			x	
Poland			x	
Slovenia	x		x	x
UK	x			x
Total	**7**	**2**	**6**	**5**

Again, we have detailed below the responses here as they help us understand the challenges faced in establishing a common GSEU methodology to characterise groundwater droughts. They are as follows:

- Austria: "time series that are irregular or miss data and unknown stresses (e.g. related to groundwater extraction and stream in- and exfiltration)"
- Belgium (VMM): "VMM uses scenario-based prediction (dry-normal-wet) for the coming month based on meteo conditions in the past. Due to climate change those scenarios might lose representativity. Using actual forecasts of meteo conditions might overcome this, but the availability of good quality forecasts with time periods of one month or longer remains an issue. "

- Czechia: "We are trying to find out how to evaluate one relatively homogeneous hydrogeological body monitored by wells with predominant seasonal fluctuations, but also by wells that are without seasonal fluctuations and react to significant recharge episodes often with a delay of several years."

- Denmark: "Handling the anthropogenic drought concept, i.e., the responses from the society/human to the drought situations that may enhanced drought impacts. For instance, how to incorporate increased groundwater abstraction for water supply due to higher water demands under drought (no data is available on appropriate resolution). Determining thresholds for normal conditions in areas with high irrigation use"

- Estonia: "One of the main challenges we face in our drought analysis is the presence of data gaps. These gaps need to be addressed before conducting thorough analyses. Additionally, some of our data series are too short to support comprehensive analyses, which limits our ability to draw long-term conclusions"

- France: "The main analysis-related challenges are about the use of probabilistic analysis for inertial water tables (with significant interannual variability), water tables with trends or even anthropogenic-influenced water tables"

- Germany: "We would like to compute and incorporate the Standardized Groundwater level Index (SGI) as planned on the GSEU project. We would like to link this analysis to the respective groundwater system"

- Ireland: "The main challenge is a lack of groundwater data. Consequently, we found it difficult to gather evidence of hydrogeological similarities across aquifer types"

- Netherlands: "Yes, a good way to include the change of normal in evaluating drought. Also, the transfer-noise modelling needs to be improved for long time series and extreme situations. Usually evaporation is energy limited in the Netherlands, but with higher temperatures and longer periods without precipitation there is a shift toward water limited evaporation"

- Poland: "Long-term forecasts are a challenge for us. Recently, inspired by the approaches presented by the group, mainly from France and Germany, we have developed a model using MDTWP for low-frequency diagnostics and predictions. However, when it comes to forecasts – there is still a lot of work to be done – these forecasts only show a general trend of change – based on low frequencies. Previously, we only used the regression curve for this type of analysis, calculated only over relatively long-term observation sequences"

- Slovenia: "One of the challenges was the lack of longer time series of groundwater levels (more than 30 years) and the non-uniform spatial distribution of the observation stations in the past. Another challenge with long time series are anthropogenically altered groundwater levels. In our study, we omitted monitoring sites with anthropogenic changes. Another problem that could not be solved in the analysis was the general statistical linear trend of the decline in the groundwater levels, which affects the varying intensity and size of the deficit of the dry periods. Due to the occurrence of a linear trend, there have been a large number of droughts in recent times. The linear trend in groundwater level fluctuations is largely the result of anthropogenic activities (construction of hydropower plants, creation of accumulation lakes, regulation of rivers and streams for irrigation purposes, etc.) and also climatic factors"

- UK: "Obtaining suitable long, high quality groundwater hydrographs. Changes in monitoring frequency. Obtaining suitable site-specific metadata related to aquifer, catchment characteristics to understand aquifer and catchment controls on groundwater response to meteorological droughts. Obtaining information on water resource management practices that may influence observations and the analysis"

- Spain (IGME), Malta, Serbia: No challenges noted

Are there additional methods you plan to use or would like to explore in the future?

Ten of the respondents indicated that they planned future developments related to groundwater drought analysis. These are detailed below:

- Austria: "A method to consider could be the Standardised Groundwater level Index (SGI) by Bloomfield and Marchant (2013)"

- Cyprus: "Autocorrelations with GWL with the aid of AI?"

- Czechia: "We plan to use time series analysis with different types of drivers, clustering and, of course, trend analysis. Even if the trends for individual types of level fluctuations are often obvious, it is necessary to find the reasons (principal drivers) for changing trends in individual environments and for individual types of groundwater level fluctuations"

- Denmark: "We would like to expand our investigation to other index types, also potentially combining remote sensing and modelling results"

- Finland: "Currently we aim to find methods to monitor the water quality in order to predict the rise in water levels and to be able to prepare Water Utilities for possible flood risk."

- France: "In future years, we plan to better characterise the impacts of groundwater droughts on aquatic environments and biodiversity"

- Ireland: "One method proposed by our consultants to be used in our 2023-2027 project is that of high and low pulse counts characterise the structure of time series with regards to the interannual variation"

- Poland: "In the future, when we automate our measurements across the entire monitoring network, we want to include precipitation and/or satellite data in forecasts in order to, for example, better determine the probability of a given scenario coming true"

- Romania: "Statistical analyses"

- UK: “Joint SPI, SSI, SGI analysis across the UK. Analysis of recession characteristics to inform our understanding of GW drought dynamics”

What are your ideas about the GSEU groundwater drought analysis for Europe?

Finally, 14 of the 24 responding surveys provide ideas related to the pan-European GSEU drought analysis. Some of the ideas are quite specific others are more general and some philosophical in nature, concerning the overall approach. They do not lend themselves to a systematic analysis, so they are simply presented below.

- Austria: “It would be great to consider GSEU drought analysis methods for us. Preferred time scales would be 6-36 months, and spatial aggregation should consider alpine catchment sizes. SPI & SPEI is usually available for 1km² grid cells”

- Belgium (VMM): “VMM is interested in enhancing its drought analysis and forecast capacity at the level of the Flemish region. Regional drought indicators that allow for easy comparison over time and/or over different regions within Europe would be welcome. “

- Cyprus: “Inevitably, hydrogeological conditions and drought scales and definitions vary across Europe. Groundwater level analysis and autocorrelation, perhaps with the aid of AI, could be developed. However, drought definition (scale of groundwater level drop), benchmark drought, and time/spatial scale should most likely be defined based on local/regional hydrogeological conditions.

- Czechia: “The first steps are, of course, the visualization of all fluctuations in groundwater levels across Europe. We definitely recommend that any trend analysis should be conducted first on a selection of wells that can be considered reliable or representative and not affected by unexplained water management and measurement errors. This approach will certainly simplify and, above all, speed up familiarization with the behaviour of groundwater levels in different parts of Europe”

- Estonia: “Regarding the GSEU, we believe that a unified methodology incorporating seasonal analysis and the differentiation between shallow and deep aquifers would be beneficial. This approach would help create a more comprehensive understanding of drought impacts across Europe, facilitating better-informed decision-making and resource management strategies”

- France: “For GSEU groundwater drought analysis, it may be great to result in a map over Europe showing the sensitivity of aquifers to drought and on what time scale (short-term, long-term)”

- Germany: “Analysis that allows identifying regions prone to drought and possible cross-border impacts to propose jointly management strategies”

- Hungary: “We are interested in drought analysis and expecting the contribution in development of a common method for groundwater drought analysis for Europe”

- Malta: “In favour and would like to follow the process, plus contribute as necessary with Malta’s data”

- The Netherlands: “Limit ourselves to analysis of measurement time series. Characterise series for all countries e.g. with (transient) SGI. It would be nice to put this in a pan-European paper similar to GeoERA-TACTIC. Try to advance separation of natural and anthropogenic influences and translation into water availability and its variation in time.

- Poland: “It's hard to say. Maybe after this survey, the goals will become more clear – at least in terms of the time step – the timeframe of the forecast or which groundwater levels the forecast is supposed to refer to – only the shallowest one or deeper?”

- Slovenia: “Calculate the annual SGI index for the first/upper aquifers to get an overall picture and then decide how to further evaluate the data more precisely (include multilayers or monthly data)”

- Spain (IGME): “We can generate a very interesting product, with a lot of potential impact on the visibility of groundwater”

- Sweden: “It could be beneficial to have a common method to calculate groundwater drought, such as SGI, in a European scale. However, I think it must be very clear that it is not directly linked to consequences since the hydrogeological conditions and the dependency of groundwater is very variable throughout Europe. So far, we have not been able to objectively include consequences for Swedish conditions despite that we are several colleagues with decades of experience within the topic”

- UK: “Have a couple of outputs. First a simple 'live' status map (similar to the one used in BGS' Hydrological Summary) for any sites with live data updated on a monthly or quarterly basis. This could include status of any site with say 5 years or more of data and would be monthly rank coded as one of seven percentile classes. The secondly approach would be SGI-based and applied at sites with more data (say ~20 years or better of data). This would be a map of SGI status that can be queried for any given date over that period (monthly time-step)”

3. Groundwater Level Trend Detection and Quantification

3.1. Literature review of approaches to groundwater level trend detection and quantification

A literature review was conducted in May 2024 to identify groundwater trend analysis methods used globally. This review primarily used the Web of Science (topic = “groundwater” AND “trend analysis” AND “methods” returning 78 results), and a second search (title = “groundwater” AND “trend analysis” returning 29 results) along with some papers which had previously been added into EndNote. After manually filtering through the articles, a total of 79 were identified as potentially useful, of which 37 were deemed as good sources (listed in Annex 2). Publication dates of the 37 papers ranges from 2006-2024, with most having been published since 2020. The literature covers groundwater trend analysis methods across the world from North America (3), Asia (23), Africa (3), Oceania (2) and Europe (4), and no specific location (1). Countries with the most groundwater trend analysis method studies were India (13), Iran (4) and China (3). Most of these papers apply groundwater trend analysis methods to real data, and at various scales but commonly at regional or basin/aquifer scales. Some use groundwater storage anomaly estimates using GRACE, Global Land Data Assimilation System (GLDAS) and numerically modelled datasets to perform trend analysis (e.g., Janardhanan et al., 2023, Ghosh and Bera, 2023). Groundwater trend analysis methods were applied to long-term datasets in all the studies, ranging from 7 to 55 years of relatively continuous data. For countries with seasonal/cyclic variations, trends were sometimes conducted individually for the different seasons (e.g., Abbas et al., 2023, for pre-monsoon and post-monsoon).

Various groundwater trend analysis methods are described, with the most common groundwater trend analysis method being the non-parametric *Mann-Kendall* (used in 27/37 papers) and the *Sen’s Slope*. The fact that the *Mann-Kendall* test is non-parametric makes it flexible and able to handle missing data, seasonality and skewed data. *Mann-Kendall* trends can detect monotonic trends, are generally analysed at 5% significance levels and 95% confidence levels and there are open-source software packages available for its use (Hussain and Mahmud, 2019). The *Mann-Kendall* method was used for time-series data exceeding 10 years in all the studies, and often for >20-year datasets. Though generally robust, its weakness is that the presence of positive serial correlation in a dataset increases the probability that *Mann-Kendall* tests detect trends when they do not exist (Hamed and Rao, 1998). Mirabbasi et al. (2020) used the *Mann-Kendall*, *modified Mann-Kendall*, *Spearman’s Rank* and Innovative Trend Analysis (ITA) and found that the *modified Mann-Kendall* test was the most appropriate method, providing the most informative results. All of the aforementioned tests can be used to detect monotonic trends, with an added potential in the ITA to detect nonlinear trends. The *modified Mann-Kendall* method was used in 4/37 studies. The *modified Mann-Kendall* (there are two versions of it, but the one proposed by Hamed and Rao (1998) is the most widely used) can handle serially correlated datasets and is therefore sometimes preferred over the *Mann-Kendall* as it removes the issue of positive serial correlation. Hamed and Rao (1998) mention: A closely related problem [to serial correlation among the observations] that has been studied is the case where seasonality exists in the data (Hirsch et al., 1982). By dividing the observations into separate classes according to seasons and then performing the Mann-Kendall trend test on the sum of the statistics from each season, the effect of seasonality can be eliminated. This modification is called the *seasonal Kendall test* (Hirsch et al., 1982, Hirsch and Slack, 1984, Zetterqvist, 1991). Although the seasonal test eliminates the effect of dependence between seasons, it does not account for the correlation in the series within seasons (Hirsch and Slack, 1984). *Sen's slope* was used in conjunction with the *Mann-Kendall* or *modified Mann-Kendall* tests in most studies as to estimate the slope and thus the magnitude of change (Hirsch et al., 1982).

A few studies used the *Spearman's Rank* non-parametric test alongside other methods such as Mann-Kendall tests, *Sen's slope* and parametric *Linear Regression Analysis* (e.g., Monir and Sarker, 2024, Mirabbasi et al., 2020). It should be noted that the two latter methods can only be used to detect linear trends. *Spearman's Rank* is used to detect the presence of monotone tendency in time-series (McGhee, 1985). Mirabbasi et al. (2020) and Citakoglu and Minarecioglu (2021) found that the *Spearman's Rank* method yielded similar trend results to the *Mann-Kendall* test. Five studies use the ITA whereby time series data is halved, then sorted in ascending order and the first half is plotted on the x-axis against the second half of the time series on the y-axis against a 1:1 line to determine increasing/decreasing monostatic trends and trends in low, medium and high values. Trend magnitudes and confidence limits can be obtained from ITA. Minea et al. (2020), Swain et al. (2022) and Abbas et al. (2023) solely used ITA, whilst others (e.g., Das et al., 2021, Mirabbasi et al., 2020) used ITA alongside other methods such as *Mann-Kendall* and *Sen's slope* for robustness of results and to determine whether the different methods agreed on the trends. (Mirabbasi et al., 2020) found that the ITA method was not as comprehensive or precise for trend analysis as it does not provide a quantitative index for identifying the significance of trends, however, Swain et al. (2022) found that the ITA does not have the same restrictions (such as Gaussian distributed time series and serial correlation issues) as *Mann-Kendall*, *Spearman's Rank* or *Sen's slope* techniques, and therefore can be used to detect trends in time series of shorter lengths. Serinaldi et al. (2020) reviewed the ITA method and called into question its correctness having found that it suffers from several theoretical inconsistencies affecting its derivation, formulas and interpretation.

For countries with seasonal/cyclic variations, trends were conducted individually for the different seasons (e.g., Abbas et al., 2023, for pre-monsoon and post-monsoon). Some studies spatially interpret trends using *Inverse Distance Weighting method*, which is often GIS based (e.g., Gautam et al., 2022). Other less used groundwater trend analysis methods identified in the literature include: the *Pettit test* used to determine change points in historical time series (e.g., Citakoglu and Minarecioglu, 2021); *Kendall's phase test*; *Kendall's rank correlation test* (e.g., Monir and Sarker, 2024); *Wald-Wolfowitz total number of runs test* non-parametric test used to evaluate if two continuous cumulative distributions are significantly different or not; *Hierarchical Cluster Analysis* (e.g., Noori and Singh, 2021, Pathak and Dodamani, 2019); *Subsample Aggregating Regression* for anomaly detection (e.g., Jeong et al., 2017); *Seasonal Trend decomposition based on Loess* used for dissecting variations in time data series across various temporal scales (e.g., Oluwaniyi et al., 2023); and *Bootstrapping* (e.g., Adombi et al., 2024).

3.2. Summary of methods used by national and state surveys and institutional needs and interest for trend analysis

The participating national and state geological surveys were invited to provide a concise description describing the potential benefits of groundwater head trend analysis to their specific needs, and, if already being conducted, the approaches being employed by each partner. Participating surveys were invited to respond even if they not are presently engaged in national-scale trend analysis since their insights in the potential applications and/or any experiences at a sub-national level would still be valuable.

The following questions were provided as prompts or guides to provide some structure to the responses:

- Are you currently interested in or undertaking national trend analysis of groundwater heads?
- What time scale (e.g., recent over-abstraction/recovery, long-term trends) are of interest to you?
- What spatial aggregation do you use?
- How do you treat multi-aquifer systems?
- If you are already using trend analysis, what methods are currently in use?
- Have you encountered any particular analysis-related challenges?
- Are there additional methods you plan to use or would like to explore in the future?
- Can you highlight any additional information such as publications, reports, or web links related to the methods you are currently employing or wish to use in the future?
- What are your ideas about trend analysis of groundwater heads for Europe?

3.2.1. Results

The request for input was sent to 31 Surveys who had previously expressed an interest in contributing to this sub-activity task. 28 of those surveys responded and their responses are available in full in Annex 4. Response numbers of answers for each question are displayed below in table format along with a summary of some points raised by the various surveys. Note that the totals in the tables below do not necessarily match the number of survey responses as individual surveys sometimes gave multiple responses (e.g. Q: what timescales are of interest? A: used seasonal and yearly time scales).

Are you currently interested in or undertaking national trend analysis of groundwater heads?
All Surveys who responded to this specific question (n=24) indicated that they are either currently undertaking groundwater level trend analysis or are interested in doing so in the future. Current analysis varied in temporal and spatial scale (see next questions).

What time scale (e.g., recent over-abstraction/recovery, long-term trends) are of interest to you?

Table 6: Number of responses relating to analysis time scales of interest.

Total number of respondents	Sub-seasonal	Seasonal	Annual	Sub-decadal	Multi-decadal
20	1	3	1	3	15

Although there was a range of responses from sub-seasonal to multi-decal time scale of interest (Table 6), the majority of the respondents (75%) agreed that multi-decal time scales are of particular interest to them in regard to trend analysis. E.g.:

- "We have time series of several-decades (some cases more than 40 years) length which enables to study of over-abstractions, descending groundwater levels due to climate change or other long/short term trends of potential anthropogenic and/or natural processes" (Hungary)

- "Geological Survey of Italy is currently undertaking a national trend analysis of groundwater heads aimed to define an Indicator of Climate Change Impact on selected groundwater bodies of the Italian territory. The time scale is focussed on long-term trends" (ISPRA, Italy)

- "Geological survey of Slovenia conducts trend analyses in various studies, mainly at the local scale. We are interested in short- and long-term groundwater level trends" (Slovenia)

What spatial aggregation do you use?

Table 7: Number of responses relating to spatial scales currently used for trend analysis.

Total number of respondents	Site-specific	Groundwater body	Regional	National
19	6	15	3	4

Similarly to the previous question, there was a range of responses from site-specific analysis to national scale (Table 7). However, the clear majority (79%) of respondents are currently using groundwater level trend analysis on groundwater body scale (often related to the reporting to the Water Framework Directive, WFD). E.g.:

- "Ukraine is keenly interested in the national trend analysis of groundwater heads due to a hydrogeological (water) catastrophe in the central part of Ukraine, resulting from the dam explosion at the Kakhovka Reservoir by the Russian aggressor." (Ukraine, UAG)

- "The national trend analysis of groundwater heads done as part of groundwater status assessment for the WFD reporting refers to all groundwater bodies in Poland" (Poland)

- "Regional clustering of piezometers allows identification of trends per hydrogeological units, jointly with an indication of the trend magnitude so adaptation measures can be proposed per area" (Germany)

- "We are currently undertaking trend analysis in different studies. Generally, these studies are done at a local scale where trend analysis is not an end in itself." (BRGM, France)

How do you treat multiple-aquifer systems

Of the 28 survey respondents, 11 indicated that they are currently considering multiple-aquifer systems in their analysis. E.g.:

- "In Poland, multi-layered water bodies, grouped into 3 complexes. The first complex comprises water layers that are shallow, phreatic and in general can be in contact with surface waters and groundwater dependent terrestrial ecosystems 2nd complex below the 1st complex, are generally confined and usually used for water supplies. The third complex are deep and in possible contact with mineral groundwaters beneath statistical analysis is done for each point separately and then a descriptive summary for each complex is formulated" (Poland)

- "Both, modelling and observational based analysis take multi-aquifer systems into consideration, but much attention (especially the observational network) is given to the shallow groundwater system" (Denmark)

- “Concerning multi-aquifer systems distinct boreholes are used to study each intercepted aquifer so that any contamination between aquifers [can] be avoided” (Romania)

If you are already using trend analysis, what methods are currently in use?

Table 8: Summary of trend analysis methods currently used by the respondents

Total number of respondents	None	Descriptive	Regression	Mann-Kendal (simple)	Mann-Kendal (modified)
25	10	3	4	4	6

Over the half of the indicated methods currently used by the surveys include either the simple or complex Mann-Kendal test (Table 8), though other approaches are also currently used, e.g.:

- “EWA is interested [in a] better understanding of how trend analysis is undertaken and allow the Agency to build sufficient capacity on such assessments.” (EWA, Malta)
- “Linear regression has been used for trend analysis of groundwater levels in major aquifer systems in the Drava and Sava river basins” (Croatia)
- “The Mann-Kendall trend test, whether or not suitable for a time series with significant autocorrelation, is used for testing the statistical significance of the trend, while the Sen’s slope (Sen, 1968) for assessing trend magnitude. Sometimes, if the trend analysis is conducted over different aquifers, the Sen’s slope is standardized by either the maximum water level fluctuation or the interquartile range” (BRGM, France)
- “Use the Kruskal-Wallis test for seasonality; determine the existence of a trend using either the seasonal Mann-Kendall test or the regular Mann-Kendal test; calculate the seasonal Sen’s slope or the Theil-Sen slope depending on the presence of seasonality” (TNO, The Netherlands)

Have you encountered any particular analysis-related challenges?

Table 9: Analysis-related challenges indicated by the respondents

Total number of respondents	Record length	Record quality	Breaks in slope	Trend attribution
17	5	8	1	5

Similarly to the challenges related to groundwater drought analysis, challenges with input data of sufficient record length and record quality are listed as the most common challenges for trend analysis (Table 9). Additionally, 29% of those who responded to this question also raised the issues of trend attribution. Other comments include e.g.:

"It is usually necessary to compare the long-term trends of several groundwater monitoring sites [where] the data series [length] varies considerably. The challenge is therefore either to exclude groundwater monitoring sites or to shorten the time period [of analysis]" (Austria).

- "Challenges most related to data frequency (missing data for longer interval, changes in data frequency)" (Hungary)
- "The main issue is attributing the trends to a physical phenomenon "What is driving this trend? Can I do anything about it?" or "Is it possible to identify a trend in relation to withdrawals? Climate change?" (BRGM, France)
- "VMM [Belgium] is looking forward to improve the ability to detect trend breaks and trend reversals in both phreatic and confined aquifers, to aggregate identified trends at e.g. the ground water body level, and to better differentiate between climatic and anthropogenic impacts on the trends in the groundwater level time series" (VMM, Belgium)

Are there additional methods you plan to use or would like to explore in the future?
A number of surveys use a variety of groundwater models to address questions related to groundwater trends, for example: "To gain insight into the proportions of natural and anthropogenic variations in the trends we use physically based models (SWAP; Kroes et al., 2017) [of] the time series. The models incorporate climatic effects on the groundwater level but ignore management-induced impacts such as groundwater abstraction" (VMM, Belgium).

[The Danish] national hydrological model (DK-Model) has been [used for] national scale climate change impact analysis [and] resulted in knowledge on spatially distributed trends in groundwater level dynamics.

What are your ideas about trend analysis of groundwater heads for Europe?
Of the 28 survey respondents, 11 provided their ideas about trend analysis of groundwater heads in Europe; e.g.:

- "Besides the challenges mentioned above it would be important to cluster the monitoring points based on the long-term trend analysis, the hydrogeological setting of aquifer types and the meteorological conditions (monitored data and RCP scenario data)." (Austria)
- "Adapting a common scientific method, looking both at the short-term and the long-term trends, is of interest" (Cyprus).
- "The first steps are, of course, the visualization of all fluctuations in groundwater levels across Europe. We definitely recommend that any trend analysis should be conducted first on a selection of wells that can be considered reliable or representative and not affected by unexplained water management and measurement errors. This approach will certainly simplify and, above all, speed up familiarization with the behaviour of groundwater levels in different parts of Europe." (Czechia)
- "With our current systems, we are mostly investigating the groundwater level trend as a result of changes in precipitation and temperature. Changes in abstractions, water demands, and land use are currently not considered, but need to be included for a holistic assessment." (Denmark)

- “Trend analysis approaches for groundwater heads in Europe should identify extreme events and regional groundwater patterns, which will help propose pan-European solutions and communicate with stakeholders.” (Germany)

- We think that discussion of trend analysis of groundwater heads for Europe is a big challenge. This is also due to the different meteo-climatic and hydrogeological scenarios and monitoring approach by each Member State. In any case, it is of main importance to share methodologies and start to establish common criteria on this matter. (Italy)

- “We should first set the goals for forecasting and clearly define water levels we want to analyse, for example, to specify the maximum depth of the top of the groundwater levels we want to include in analysis” (Poland).

- “Trend analysis estimation method will be of high interest to reveal patterns of change in aquifers recharge and discharge [and] monitoring the trend of piezometric levels facilitates the identification of areas at risk of water depletion, enabling the implementation of preventive and corrective measures” (ICGC, Spain-Catalonia)

- “Mapping sites or regions that show either relatively natural trends and that show trends inferred to be impacted by groundwater over abstraction or rebound would be helpful in an assessment of the vulnerability of groundwater systems to drought” (BGS, UK).

4. Approaches of Groundwater Performance Indicators to Manage Drought

The aim of this section is to describe the approaches that will be applied to identify vulnerable and resilient aquifers for droughts. In accordance with the definitions provided within the introduction, those aquifers with lower vulnerability (higher resilience) will be strategic resources to face droughts, and those one with higher vulnerability should be protected to reduce the impacts on them.

Approaches at two different spatial resolutions will be used, at head observation point and at a lumped groundwater body mass/aquifer scale. They will be defined based on different simple indices, concepts and information related to the management and/or quantification of groundwater droughts and correlation structures in groundwater level time series. Considering that there are different aspects that should be considered to study groundwater resilience to drought, and there is not a clear consensus in the scientific approach to be applied, we propose to collect evidence from different approaches to arrive at more robust conclusions. Finally, the robustness of the groundwater resilience to drought will be analysed by exploring agreements between the different assessments.

4.1. Proposed approaches at head observation point: hypothesis and limitations

At head observation point scale, there is a well-established literature on different environmental performance indicators defined from SGI time series to analyse concepts related to groundwater sustainability under drought (Neves, 2024). In this task we propose the estimation of the following indicators: Reliability, resilience and vulnerability indicators.

Loucks (1997) developed a theoretical framework to quantify the sustainability of water resources systems and illustrated it with a range of water resource management scenarios that included water storage and groundwater use. Specifically, they developed three criteria for reliability (REL), resilience (RES) and vulnerability (VUL) that could be applied to water resource performance indicators (such as SGI). Mays (2013) subsequently used these three criteria of Loucks (1997) and proposed a fourth related measure for a groundwater Sustainability Index (SI). Thomas (2019) and Neves (2024) have subsequently used these criteria to evaluate adaptive management scenarios for groundwater in the Central Valley of California, and in a drought assessment in semi-arid coastal aquifers of southern Portugal, respectively. For a certain drought threshold (fail criteria), the four criteria are defined and estimated as follows with details in the cited publications (Loucks, 1997):

- Reliability (REL): it refers to how likely a system is to not fail (defined by the adopted drought threshold). It can be obtained dividing the number of satisfactory conditions by total number of time intervals (conditions), which is equivalent to the complementary of the fail frequency. Note that when this calculation is applied to a normalised metric such as the SGI, the REL, for any specified threshold, can be determined directly from the cumulative distribution function of the metric. However, for consistency with previous work, a general calculation of REL is included here.

Two different approaches/definitions have been considered to assess resilience:

- Resilience 1 (RES 1): It is defined as the capacity to return to satisfactory conditions from failure.

- It is obtained dividing the number of times a satisfactory condition follows an unsatisfactory condition by the total number of unsatisfactory conditions.

- Resilience 2 (RES 2): It is defined as an index of how quickly the system recovers from failure. It is obtained as the inverse of the mean drought duration.

Two different approaches/definitions have been considered to assess vulnerability:

- Vulnerability (VUL 1): It is a probabilistic measure accounting for the extent and magnitude of an unsatisfactory condition. It is obtained as the summation of the magnitude (or severity) of the unsatisfactory conditions multiplied by the probability of that magnitude during the span of the timeseries (See an example in Neves, 2024).

- Vulnerability (VUL 2): The maximum significant autocorrelation (mmax), which can be used as a relative measure of memory in the groundwater status time series (Bloomfield and Marchant, 2013). They assumed that sites with shorter groundwater memories, i.e. lower values of mmax, are less vulnerable to droughts, and, conversely, those with higher values of mmax (with longer memories) are more vulnerable to drought. The concept of groundwater memory (defined by autocorrelation of groundwater level time series) has already been used in the Republic of Ireland to assess groundwater susceptibility/vulnerability to drought (Scheler et al., 2022).

These assessments will be done in those head observation points in which the data available allows to perform a statistical analysis of droughts. Finally, we will perform a statistical, geostatistical or cluster analysis of the indices obtained in each head observation point to withdraw conclusions about their spatial distribution with different spatial resolutions, including lumped groundwater body scale and/or a more detailed semi-distributed analyses of homogeneous areas.

4.2. Proposed approaches at groundwater body scale: hypothesis and limitations

In general, groundwater resources, because of their greater inertia than surface water, are strategic resources to face droughts by intensifying temporarily pumping in a context of growing scarcity. Nevertheless, some aquifers are more vulnerable than others to temporal increase of pumping, and, therefore, their potential use to adapt to droughts under scarcity conditions is lower due to their lower resilience under these circumstances (Pulido-Velazquez et al., 2020).

Previous studies have shown that the variable groundwater mean residence time is a good indicator of the aquifer resilience to temporal increase of pumping and the pollution risk (Baena-Ruiz et al., 2021). The mean residence time can be estimated by applying different approaches. In this activity we propose the use of a simple index, the Turn Over Time index (T), to perform a preliminary assessment of the mean residence time defined as the storage capacity (S) divided by the mean recharge (R) (Pulido-Velazquez et al., 2020). This approach is base in the next assumptions:

- An approach of the natural mean groundwater renewable time, the T index, is used to assess groundwater resilience to temporal increase of pumping assuming that the aquifer management allows to keep invariant the long term natural mean reserves (the mean S) of the GW bodies, and the actual recharge is the main inflow of groundwater resources.

- A parallelism between unconfined aquifers and reservoirs is adopted to approach the mean residence time. Analogies between an unconfined aquifer and a reservoir have been previously adopted to approach different stream-aquifer interaction problems [Pulido-Velazquez et al., 2007].
- In order to estimate the natural mean groundwater renewable time, we assume that there are no changes in Land Use and Land Cover, no pumping, and the net GW discharge will start when the GW storage reaches the level of the surface connection (spring, streambed, river level, or sea level boundary condition; See Figure 1.

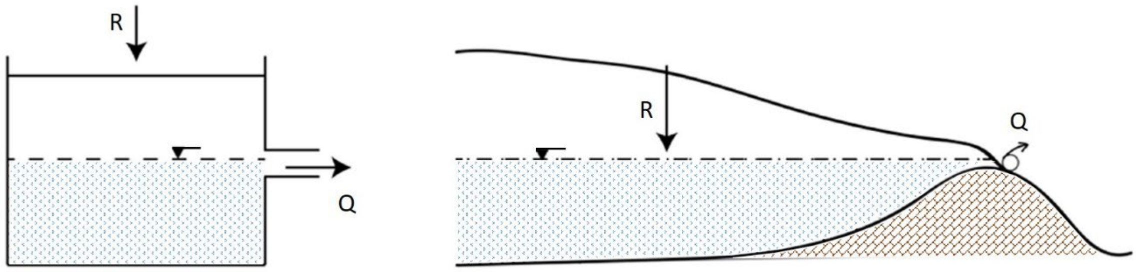

Figure 1: Conceptual approach of the T index to assess mean residence time

The application will be performed at national scale in two countries, Denmark and Spain. In Denmark the data for the S and R values in each groundwater body were withdrawn from national numerical model simulations. In Spain, the S and R data comes from recent hydrogeological studies performed for the Spanish Directorate of Water.

Finally, a preliminary analysis of the robustness of groundwater resilience to drought estimates will be performed by exploring agreements between the different assessments based on head observation point series and the T lumped index.

5. Recommendations for Workflows for Drought Characterisation and Trend Analysis

5.1. Overview of outputs

Before considering the recommendations for groundwater drought characterisation and trend analysis workflows, it is useful to summarise the key proposed high-level outputs for this activity. They are as follows:

- Graphical representation and semi-quantitative / quantitative assessment of **groundwater drought at sites across Europe**, including outputs that
  - provide an indication of the **status of groundwater resources at sites across Europe**,
  - **data and information related to groundwater drought histories at sites across Europe**, and
  - data on key **indices of vulnerability to groundwater drought** that directly contribute to the analysis of groundwater performance indicators,
- Graphical representation and assessment of semi-quantitative / quantitative **trends in groundwater levels at sites across Europe.**

5.2. Principals underlying recommendations

A number of broad principals have been developed to inform planning of the proposed workflows. These have been developed after the review of current approaches to groundwater drought analysis (Section 2) and groundwater level trend analysis (Section 3) and in the context of feedback from National and State Surveys following responses to two questionnaires and during a series of on-line workshops.

The broad principals underlying the recommendations are as follows:

- Given the complexity and spatial variability of underlying geology and catchment characteristics across Europe combined with uncertainty and variability of site, borehole, aquifer and water resource management metadata associated with the groundwater level time series; it is not considered appropriate to attempt to perform spatial aggregation of the groundwater level data. Consequently, **the workflows should focus on analysis and status of groundwater level data at points only** (e.g. at observation boreholes, piezometers, piezometer nests or arrays at a single site, wells etc).
  - Note however, the use of cluster analysis which can support the characterisation of time series with similar temporal patterns is not precluded from the workflows.
- **Groundwater level time series should be analysed from as many sites across Europe as possible** to maximise use of available data and to maximise spatial coverage of those observations across Europe.
  - This may mean using a two-tiered methodology: with a relatively simple methodology enabling as many sites as possible, including those with fewer observations and / or shorter records, to be included in a common analysis, followed by a second more robust, data-demanding method applied to a sub-set of sites with suitable records, length, density and quality.

- For a given output, **a consistent methodology or methodologies within the workflow** are to be used that enables visual and semi-quantitative and or quantitative comparison between sites across Europe.
- **There will be no use of methods that are tailored to specific areas, regions or states across Europe**.
    - Note that this principle does not preclude National or State Surveys continuing to use other methods that may be integral to their organisational responsibilities and needs.
- It is preferable to **use a method(s) that are already available, being deployed, and ideally that have already been described in a citable publication(s).**
    - The workflow should hence avoid develop new methods of analysis of groundwater drought or groundwater level trend analysis.

5.3. Recommended high-level workflow

The recommended high-level workflow for both drought characterisation and trend analysis of groundwater levels is illustrated in Figure 2 and described below. Although some specific details of the workflow are given, these will be subject to revision during refinement of the workflows once the groundwater time series data becomes available from the GSEU subtask on transnational, harmonised data gathering in early 2025. Also note that for any of the following analysis procedures, it is assumed that a quality check of the data from the GSEU subtask on transnational, harmonised data gathering in early 2025 (which will be collated in the EUGM database) has already been undertaken and / or if additional QA procedures are required, these will be integrated into the workflows described in Figure 2.

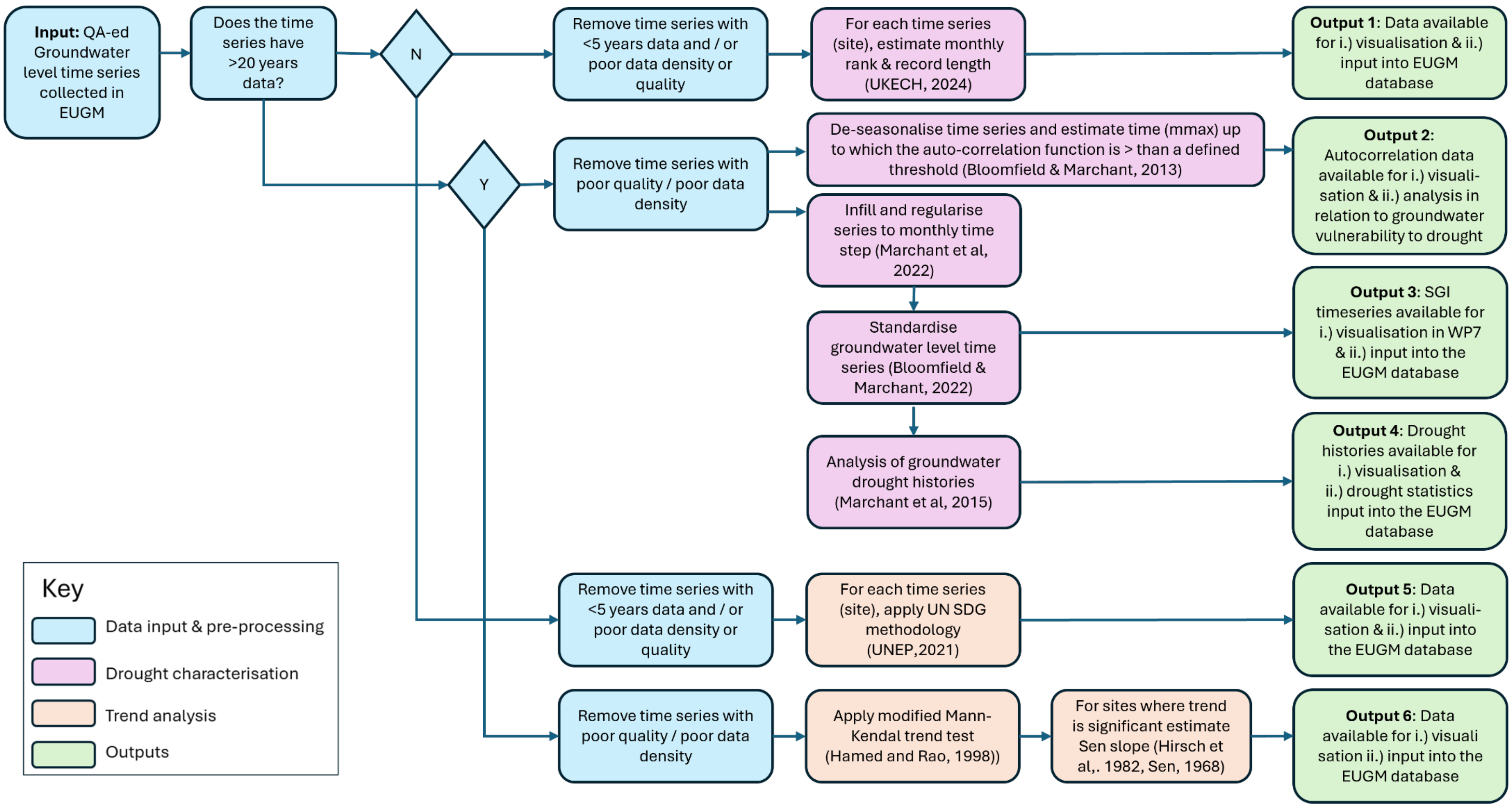

Figure 2: High-level workflows for drought characterisation and trend analysis.

5.4. Recommended drought characterisation workflow

For groundwater drought characterisation the following high-level workflow is proposed:

- Use groundwater level time series data and metadata provide by the GSEU subtask on transnational, harmonised data gathering.

5.4.1. Output 1: Monthly ranking & summary of record length for data visualisation

  - Provide data outputs for visualisation. Visualisation should be available on a monthly timestep for the period of available data.
  - Report results as tabulated records to be held in the EUGM database

- Discount all sites with <5 years of date and / or with poor data density or large data gaps (note, details of suitable data density or acceptable data gaps have yet to be established).
- For all sites with >5 years of data and good data density and limited data gaps (see note above), follow the UK Monthly Hydrological Summary methodology for groundwater level status (UKECH, 2024).
  - The UK Monthly Hydrological Summary methodology takes median monthly values of groundwater level at a given site and estimates the monthly rank of the groundwater level. This is then graphically illustrated by a point on a map showing it as being in one of seven colour-coded classes (Exceptionally high (>95%tile); Notably High (87-95%tile); Above normal (72-87%tile); Normal 28-72%tile); Below Normal (13-28%tile); Notably low (5-13%tile); and, Exceptionally low (<5%tile)) with the rank and length of record superimposed in numerals on each site, and, where the monthly ranking is a record high or record low this is also designated graphically with an additional circle round the colour-coded symbol at a site. These rankings will provide a basic graphical pan-European comparative description of the status of groundwater levels on a site-by-site basis. However, they are designed only as a qualitative, visual indicator. However, ranking at extreme levels and when levels are changing rapidly need to be interpreted with caution. Consequently, a short note on the methodology and limitations to interpretation of the ranked groundwater levels should be made available along with the visual representation of the data outputs.

5.4.2. Output 2: Information on autocorrelation of the time series

  - Report results as tabulated records to be held in EUGM database
  - Provide data to contribute to the characterisation of groundwater vulnerability to drought across Europe

- For the same sites with >20 years of data, de-seasonalise the groundwater level time series
- For these sites, estimate the autocorrelation function and maximum autocorrelation value of the deseasonalised groundwater level time series at a given site in a manner similar to that described in (Bloomfield and Marchant, 2013).

5.4.3. Output 3: Standardised groundwater level index (SGI) time series

  - Provide SGI time series data outputs for visualisation as part of the GSEU project. Visualisation should be available on a monthly timestep for the period of available data.
  - Report results as tabulated records to be held in the EUGM database.

- For all sites with >20 years of data and good data density (previously >50% availability of monthly measurements, but this could be variable) with limited data gaps (see note above), use the method developed by (Marchant et al., 2022) to infill, and regularise groundwater levels to a monthly time-step. Note that infilling time series will have some influence on derived outputs; however, when calculating SGI, it is a necessity to infill any missing data. To minimize the impact of infilling data, the above-mentioned requirement on data density will be implemented.
- Using the standardised time series, characterise groundwater drought histories using methods described in Bloomfield et al. (2015). Perform cluster analysis on the standardised groundwater level time series and for each cluster extract the following drought statistics: groundwater drought event start date and end date, event duration, magnitude and intensity.

5.4.4. Drought histories

  - Provide data on site cluster membership for visualisation as part of the GSEU project.
  - Report results of drought statistics for each cluster as tabulated records to be held in the EUGM database.

5.5. Recommended trend detection workflow

For groundwater level trend analysis, the following high-level workflow is proposed, using the groundwater level time series data provide by the GSEU subtask on transnational, harmonised data gathering.

5.5.1. Output 5: Information on trends detected via UN SDG methodology

  - Provide data outputs of the tests for visualisation as part of the GSEU project.
  - Report results as tabulated records to be held in the EUGM database
- Discount all sites with <5 years of date and / or with poor data density or large data gaps (note, details of suitable data density or acceptable data gaps have yet to be established).
- For all sites with >5 years of data and with good data density, apply the UN SDG methodology for Sub-Indicator 5 of Goal 6.6.1 that relates to changing quantity of groundwater within aquifers. The procedure is defined in the UNEP report on monitoring methodologies for that sub-indicator (UNEP, 2021) and is defined as the change in mean groundwater levels, averaged over a five-year period, from a mean in levels over a previous five-year reference period.

5.5.2. Output 6: Information on trends detected via Man-Kendall and Sen' slope test

  - Provide resulting data outputs for visualisation in as part of the GSEU project.
  - Report results as tabulated records to be held in EUGM database
- For all sites with >20 years of data and good data density apply the modified Mann-Kendal (Hamed and Rao, 1998) and Sen slope tests (Hirsch et al., 1982, Sen, 1968). These tests should be applied to median monthly values of groundwater levels and using annual average values (based on calendar years). [Note that additional analyses options could be considered at a later stage based in trends in maximum and minimum monthly and / or annual values. In addition, depending on the data available from the EUGM database, where there are very long records, in excess of ~60 years, Modified Mann-Kendal and Sen slope tests could be applied to 20- or 30-year segments of the whole time series.]

6. Recommendations for the analyses of groundwater performance indicators

6.1. Overview of the activity

Before considering the recommendations proposed to perform the identification of vulnerable and resilient aquifers for droughts, it is useful to summarise the key proposed high-level outputs for this sub-activity. They are as follows:

- Graphical representation and semi-quantitative / quantitative assessment of **groundwater historical performance indicators (reliability, resilience and vulnerability) at sites across Europe (head observation points)**, based on the SGI series produced in the drought characterisation work.
- Graphical representation and assessment of semi-quantitative / quantitative **resilience** based on a preliminary assessment of the mean residence time at groundwater body scale. Results at national scale in Spain and Denmark will be included.
- Graphical representation and assessment of semi-quantitative / quantitative robustness of aquifer resilience assessment based on the results obtained by applying different approaches.

6.2. Principles underlying recommendations

- A number of broad principles have been developed to inform planning of this workflow. They have been developed after the review of concepts and current approaches to identify vulnerable and resilient aquifers for droughts (see Section 4). The broad principals underlying the recommendations are as follows: The proposed performance indicators to manage droughts should be analysed from as many sites across Europe as possible to maximise use of available data and to maximise spatial coverage of those observations across Europe. It should be applied in all the sites in which the drought analysis is performed.
- For a given output, **a consistent methodology or methodologies within the workflow** is to be used that enables visual and semi-quantitative and/or quantitative comparison between sites across Europe (see Figure 3).
- At point scale, an analysis of robustness of the resilience and vulnerability assessment obtained with the two different proposed approaches will be performed. In the study of the resilience the robustness analyses will be also extended to groundwater body scale, exploring the agreement of the assessment at head observation point and at groundwater body scale by applying the proposed T index approach.

6.3. Recommended high level workflow

The suggested high-level workflow for the analysis of groundwater performance indicators is presented in Figure 3.

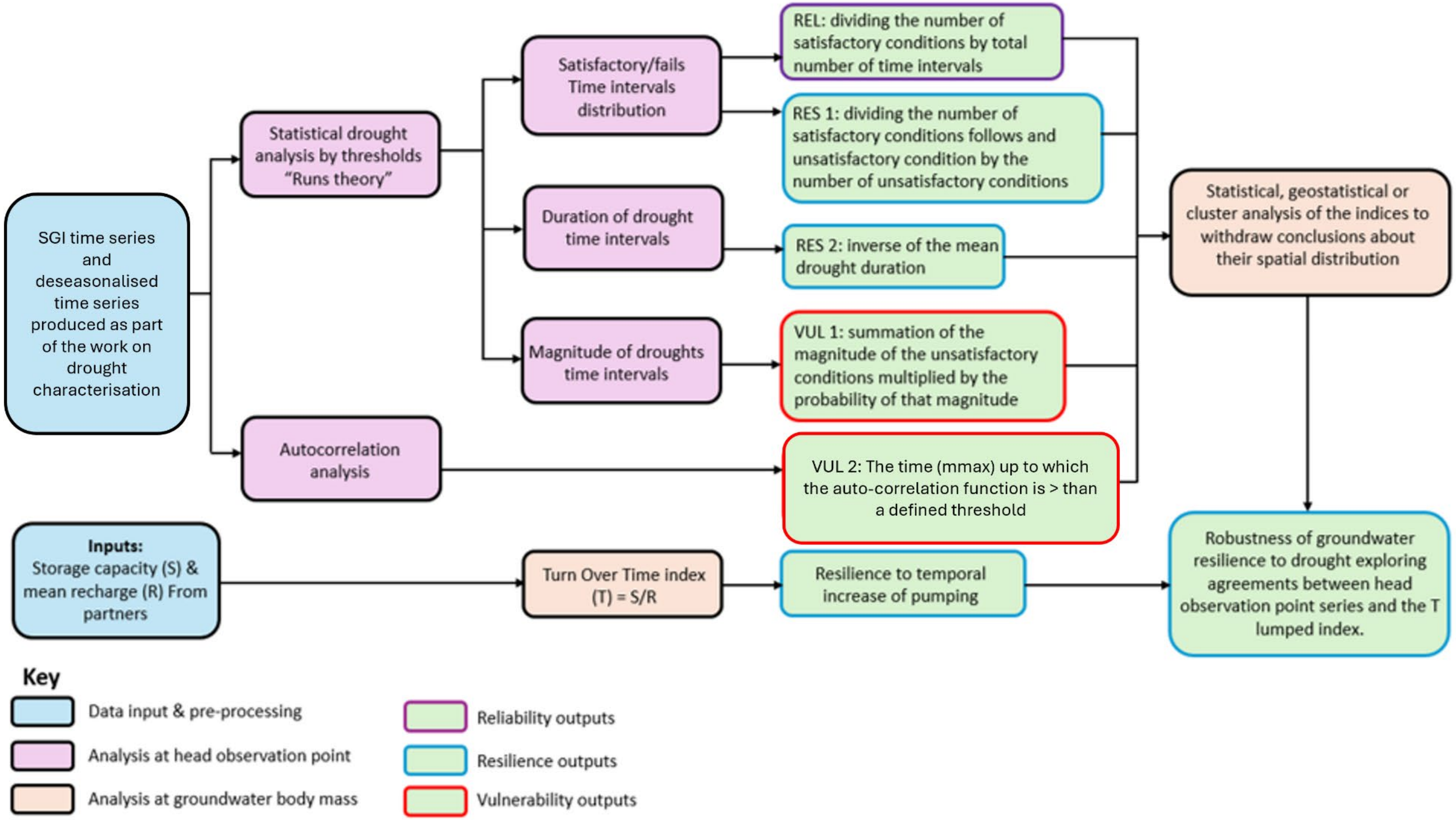

Figure 3: High-level workflows for the analyses of groundwater performance indicators.

7. Conclusion

This Deliverable provides a description of the methodological approaches that will be applied to study the dynamic of groundwater status, which will allow us to generate a catalogue of vulnerable and resilient aquifers for droughts. The final outcomes of the deliverables are the description of the approaches that we aim to apply for: 1. Groundwater Drought identification and characterization; 2. Groundwater level trend and quantification, and 3. Groundwater performance indicators of resilience and vulnerability. They will be based on the information withdrawn from an intensive literature review and Surveys provided by the different European Geological Surveys, which allow us to identify the available information in each EU country that can be used for the generation of the product at EU scale. The final “catalogue of vulnerable aquifers” will be implemented on the European Geological Data Infrastructure (EGDI) platform.

A review of literature on drought characterisation in Europe, and analysis of questionnaires on the current use and needs for groundwater drought characterisation by the European Surveys indicated the SGI as a useful indicator to characterise groundwater drought. Hence, the SGI will be used to analyse data with sufficient time series length (c. >20 years) and sufficient data quality that is being collected within the EUGM database. The analysis will be complemented by estimating autocorrelation values of the time series, which will feed into the analysis of groundwater sites that are more resilient to droughts, and cluster analysis on the standardised groundwater level time series and for each cluster extract the following drought statistics: groundwater drought event start date and end date, event duration, magnitude and intensity. To enable the use of shorter time series (c. >5 years), a 2-tiered approached is used, and the ranked status of groundwater levels (following a methodology used in the UK Monthly Hydrological Summaries, UKCEH, 2024) will be indicated.

A review of literature on trend analysis, and analysis of questionnaires on the current use and needs for trend analysis by the European Surveys indicated the modified Mann-Kendal (Hamed and Rao, 1998) and Sen slope tests (Hirsch et al., 1982, Sen, 1968) as a useful approach to be used for trend analysis of those data within the EUGM of sufficient time series length (c. >20 years) and sufficient data quality. To enable the use of shorter time series (c. >5 years), a 2-tiered approached is used, and the UN SDG methodology for Sub-Indicator 5 of Goal 6.6.1 that relates to changing quantity of groundwater within aquifers will be used (UNEP, 2021).

A review of the literature of groundwater performance indicator has been performed (Loucks, 1997; Thomas, 2019). Approaches at two different spatial resolutions will be used, at head observation point (Neves, 2024) and at a lumped groundwater body mass/aquifer scale (Pulido-Velazquez et al., 2020). The head observation point approaches will be defined based on different simple indices, concepts and information related to the management and/or quantification of groundwater droughts and correlation structures in groundwater level time series. Considering that there are different aspects that should be considered to study groundwater resilience to drought, and there is not a clear consensus in the scientific approach to be applied, we propose to collect evidence from different approaches to arrive at more robust conclusions. Finally, the robustness of the groundwater resilience to drought will be analysed by exploring agreements between the different assessments.

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9. Annex I – Consortium Partners

Consortium partners			
	Partner Name	**Acronym**	**Country**
1	EuroGeoSurveys	EGS	Belgium
2	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek	TNO	Netherlands
3	Sherbimi Gjeologjik Shqiptar	AGS	Albania
4	Vlaamse Gewest	VLO	Belgium
5	Bureau de Recherches Géologiques et Minières	BRGM	France
6	Ministry for Finance and Employment	MFE	Malta
7	Hrvatski Geološki Institut	HGI-CGS	Croatia
8	Institut Royal des Sciences Naturelles de Belgique	RBINS-GSB	Belgium
9	Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy	PGI-NRI	Poland
10	Institut Cartogràfic i Geològic de Catalunya	ICGC	Spain
11	Česká Geologická Služba	CGS	Czechia
12	Department of Environment, Climate and Communications - Geological Survey Ireland	GSI	Ireland
13	Agencia Estatal Consejo Superior de Investigaciones Cientificas	CSIC-IGME	Spain
14	Bundesanstalt für Geowissenschaften und Rohstoffe	BGR	Germany
15	Geološki zavod Slovenije	GeoZS	Slovenia
16	Federalni Zavod za Geologiju Sarajevo	FZZG	Bosnia and Herzegovina
17	Istituto Superiore per la Protezione e la Ricerca Ambientale	ISPRA	Italy
18	Regione Umbria	-	Italy
19	State Research and Development Enterprise State Information Geological Fund of Ukraine	GIU	Ukraine
20	Institute of Geological Sciences National Academy of Sciences of Ukraine	IGS	Ukraine
21	M.P. Semenenko Institute of Geochemistry, Mineralogy and Ore Formation of NAS of Ukraine	IGMOF	Ukraine
22	Ukrainian Association of Geologists	UAG	Ukraine
23	Geologian Tutkimuskeskus	GTK	Finland
24	Geological Survey of Serbia	GZS	Serbia
25	Ministry of Agriculture, Rural Development and Environment of Cyprus	GSD	Cyprus
26	Norges Geologiske Undersøkelse	NGU	Norway

27	Latvijas Vides, ģeoloģijas un meteoroloģijas centrs SIA	LVGMC	Latvia
28	Sveriges Geologiska Undersökning	SGU	Sweden
29	Geological Survey of Denmark and Greenland	GEUS	Denmark
30	Institutul Geologic al României	IGR	Romania
31	Szabályozott Tevékenységek Felügyeleti Hatósága	SZTFH	Hungary
32	Eidgenössisches Departement für Verteidigung, Bevölkerungsschutz und Sport	VBS (DDPS)	Switzerland
33	Elliniki Archi Geologikon kai Metalleftikon Erevnon	HSGME	Greece
34	Laboratório Nacional de Energia e Geología I.P.	LNEG	Portugal
35	Lietuvos Geologijos Tarnyba prie Aplinkos Ministerijos	LGT	Lithuania
36	Geologische Bundesanstalt	GBA	Austria
37	Service Géologique de Luxembourg	SGL	Luxembourg
38	Eesti Geoloogiateenistus	EGT	Estonia
39	Štátny Geologický ústav Dionýza Štúra	SGUDS	Slovakia
40	Íslenskar Orkurannsóknir	ISOR	Iceland
41	Instituto Português do Mar e da Atmosfera	IPMA	Portugal
42	Jarðfeingi	Jardfeingi	Faroe Islands
43	Regierungspräsidium Freiburg	LGRB	Germany
44	Geologischer Dienst Nordrhein-Westfalen	GD NRW	Germany
45	Landesamt für Geologie und Bergwesen Sachsen-Anhalt	LfU	Germany
46	Vlaamse Milieumaatschappij	VMM	Belgium
47	Norwegian Petroleum Directorate	NPD	Norway
48	United Kingdom Research and Innovation - British Geological Survey	UKRI-BGS	UK

10. Annex II – Literature Review 1 - Groundwater Drought Characterisation

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11. Annex III – Literature Review 2 - Trend Analysis

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12. Annex IV – National Approaches to Groundwater Drought Identification and Characterisation

Austria

What is your definition of drought?
The deviation of the current groundwater level (e.g. daily basis) to the mean groundwater level of the reference period is considered to classify water levels into categories. Based on this, values with -25 and -100% are classified as low groundwater levels and values with a negative deviation of -100% are classified as very low.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?
Examples are the extreme years 2003 and 2018 that could be used as a benchmark.

Are you currently interested in or undertaking national or sub-national drought analysis?
We face particularly in the northern and eastern regions of Austria commonly years in which groundwater recharge is below 50% of the long-term average during dry periods. Conditions can be even worse on a small-scale and seasonal basis.
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Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
We consider time series analysis and response functions (including auto- and cross-correlation).

If you are already undertaking drought analysis, what methods are currently in use?
We commonly use the Standardized Precipitation Index (SPI) to characterize meteorological droughts and the Standardized Precipitation Evapotranspiration Index (SPEI) as a preferred extensions using evapotranspiration (ET) approaches adapted for Austria.

Have you encountered any analysis-related challenges?
Analysis related challenges to consider are time series that are irregular or miss data and unknown stresses (e.g. related to groundwater extraction and stream in- and exfiltration).

Are there additional methods you plan to use or would like to explore in the future?
A method to consider within GSEU could be the Standardised Groundwater level Index (SGI) by Bloomfield & Marchant (2013).

What are your ideas about the GSEU groundwater drought analysis for Europe?
Currently we are conducting projects focusing on the analysis of groundwater availability in the Southern Basin of Vienna and the cross-border region Austria/Czech Republic. It would be great to consider GSEU drought analysis methods for us. Preferred time scales would be 6-36 months, and spatial aggregation should consider alpine catchment sizes. SPI & SPEI is usually available for 1 km² grid cells.

Belgium-Flanders

What is your definition of drought?
In Flanders the Flemish Drought Commission communicates about the current drought situation. It uses 4 drought levels that represent the type of reactive drought measures in place at that moment (0 = no measures/drought; 4 = crisis coordination by provincial or federal governments). In order to consider appropriate actions, stakeholders and governments have access to an internal dashboard of drought indicators among which are phreatic groundwater level indicators. The latter are based on current distribution of percentiles of groundwater levels for the time of the year for a set of phreatic groundwater monitoring wells. A common indicator for (meteorological) drought is the precipitation deficit over the growing season (P-PET from April 1st to September 30th), as well as standard

precipitation/evapotranspiration indices over 1-month of 3-month periods (SPI and SPEI for 1, 3, 6, 12-month periods). The Standardized Groundwater Index (SGI) could be used in future drought evaluation.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?

Based on the precipitation deficit over the growing season the years with the worst droughts in Belgium since 1900 are: 1921, 2020, 2018, 1959 and 1976. The summer of 1976 marks the worst drought in Flanders' collective memory, whereas July and August 2022 had the lowest amount of precipitation since the start of the observations in 1833.

Are you currently interested in or undertaking national or sub-national drought analysis?
If you are already undertaking drought analysis, what methods are currently in use?
Currently Flanders Environment Agency (VMM) mostly focusses on the phreatic groundwater above the main aquitards in Flanders' subsoil. For a set of selected phreatic groundwater wells physical (SWAP) or timeseries analysis (pastas) models for the past 30-year periods (or a fixed 30-years reference period) are built (calibration + data assimilation procedures).

Daily groundwater levels at the monitoring point level are classified in percentile classes with regard to the 30-years reference period: absolute comparison to the whole 30-years period and relative comparison with regard to the same day of the year in the reference period (e.g. https://www.dov.vlaanderen.be/page/grondwaterstandindicator-02-07-2024).

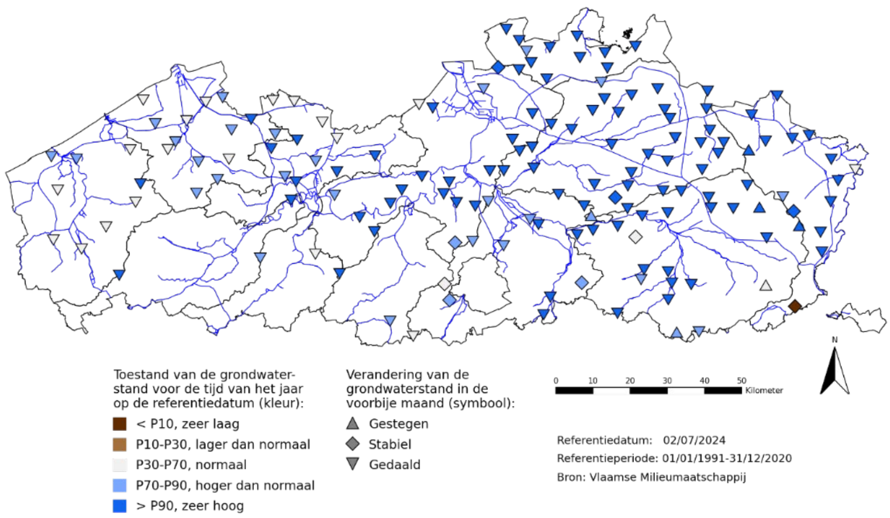

Figure A3 1. Percentile classes of groundwater levels in Belgium. Source: Actuele grondwaterstandsindicator, https://www.dov.vlaanderen.be/page/actuele-grondwaterstandindicator, Databank Ondergrond Vlaanderen, consulted on July 15th, 2024.

The distribution of the monitoring wells over the different percentile classes gives an idea about the deviation from normal (absolute or relative) for a certain date, and its evolution.

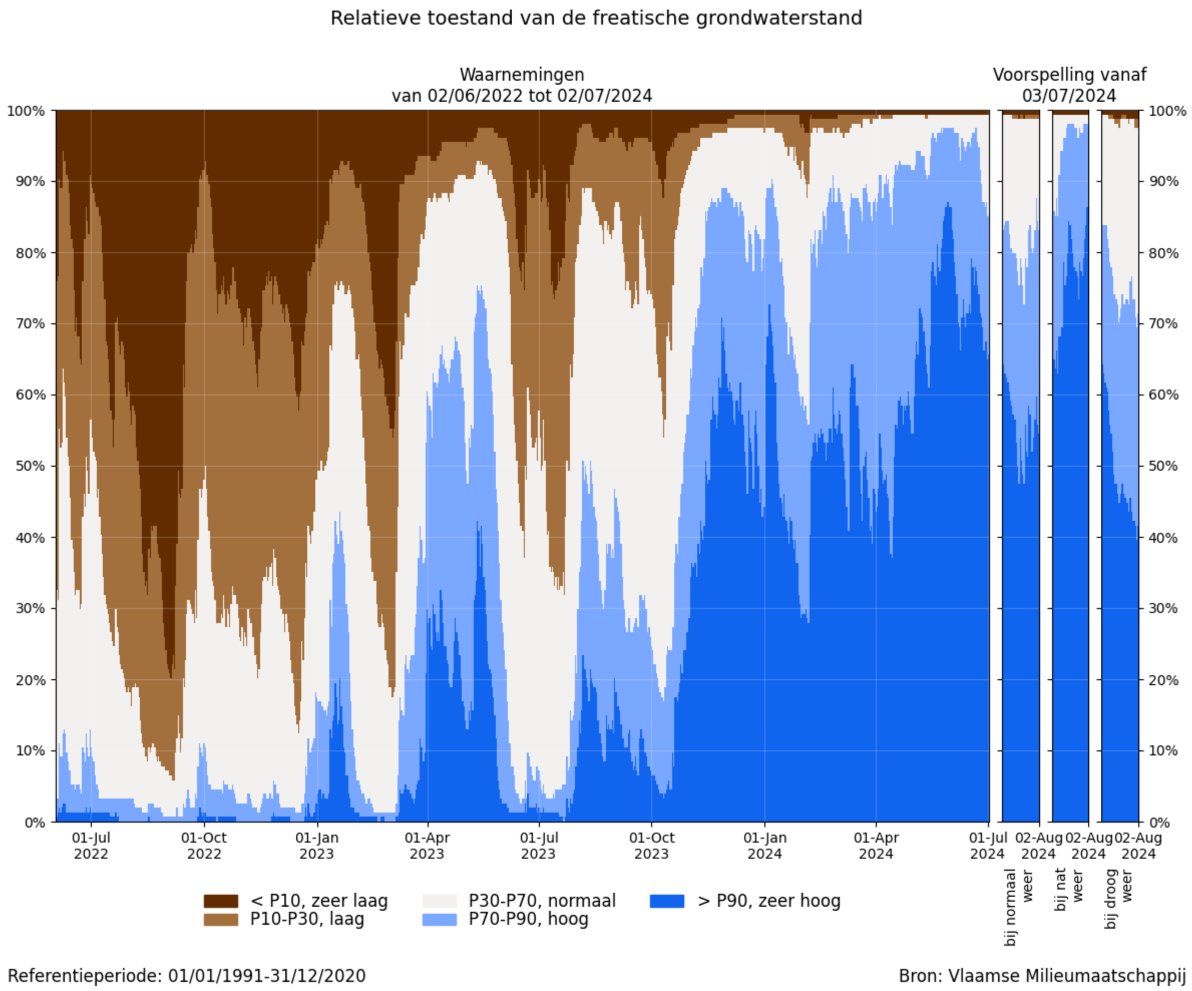

Figure A3 2. Distribution of the differences between mean groundwater level per season the mean groundwater level. Source: Actuele grondwaterstandsindicator, https://www.dov.vlaanderen.be/page/actuele-grondwaterstandindicator, Databank Ondergrond Vlaanderen, consulted on July 15th, 2024.

To quantify the deviation from normal we show the distribution of the differences between mean groundwater level per season (or week, month) and the mean groundwater level for that season over the reference period.

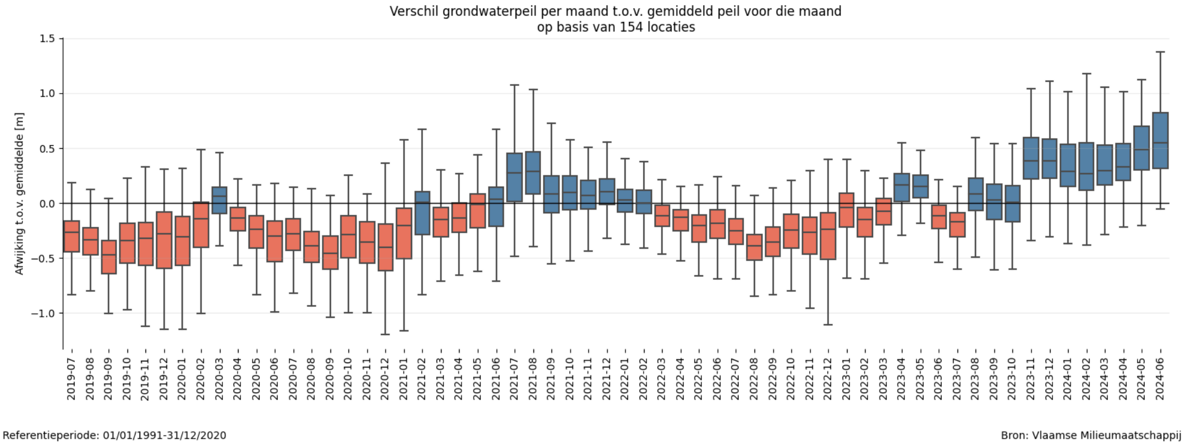

Figure A3 3 Mean monthly groundwater level of 154 monitoring stations over time. Source: Actuele grondwaterstandsindicator, https://www.dov.vlaanderen.be/page/actuele-grondwaterstandindicator, Databank Ondergrond Vlaanderen, consulted on July 15th, 2024.

To relate drought in Flanders to other regions in Europe VMM currently looks at the Grace-based Shallow Groundwater Drought Indicator maps for Europe (https://nasagrace.unl.edu/).

Have you encountered any analysis-related challenges?
VMM uses scenario-based prediction (dry-normal-wet) for the coming month based on meteo conditions in the past. Due to climate change those scenarios might lose representativity. Using actual forecasts of meteo conditions might overcome this, but the availability of good quality forecasts with time periods of one month or longer remains an issue.

What are your ideas about the GSEU groundwater drought analysis for Europe?
VMM is interested in enhancing its drought analysis and forecast capacity at the level of the Flemish region. Regional drought indicators that allow for easy comparison over time and/or over different regions within Europe would be welcome.

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https://www.dov.vlaanderen.be/portaal/?module=verkenner&bm=fa0a5241-2510-4471-9174-8a6ad5b3a7b8 – interactive map for most recent situation

https://www.integraalwaterbeleid.be/nl/overleg/droogtecommissie - Drought communication by Flemish Drought Commission (in Dutch)

Corluy J. Flanders' Phreatic Groundwater Level Indicator: update & Effect of Climate Change on phreatic GW in Flanders. Presentation at Study Day 2023 "Drought: what impact on groundwater resources in Belgium?", IAH Belgium, 9/6/2023.

Croatia

What is your definition of drought?

Croatian Meteorological and Hydrological Service use the standardized precipitation index, SPI (Standardized Precipitation Index), developed by McKee et al. (1993), and recommended by the World Meteorological Organization (Hayes et al., 2011; WMO, 2012). From 2023, the monitoring of draught in Croatia is supplemented with the standardized precipitation-evapotranspiration index (SPEI) (Vicente-Serrano et al. 2010), which is based on the difference between the amount of precipitation and potential evapotranspiration, which is calculated using the mean minimum and maximum air temperature (www.meteo.hr).

Are you currently interested in or undertaking national or sub-national drought analysis?
HGI-CGS currently is not involved in drought analysis.

Cyprus

What is your definition of drought?
Standardized Precipitation Index (SPI)<-0.99, RI<50% and a discernible drop in GWL(s).

Are you currently interested in or undertaking national or sub-national drought analysis?
Yes, we are interested but there is a lack of resources in undertaking this endeavour.

What time scales are of interest to you?
Years

What spatial aggregation do you use?
Water body

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
No but we should.

Do you consider droughts in multi-aquifer systems and, if so, how?
Multi-aquifer systems, in our case, is mostly in highly fractured ophiolites and it is considered as a unified system.

If you are already undertaking drought analysis, what methods are currently in use?
Groundwater levels, from our telemetric monitoring network, are evaluated yearly and compared manually with that of the previous year(s).

Are there additional methods you plan to use or would like to explore in the future?
Autocorrelations with GWL with the aid of AI?

What are your ideas about the GSEU groundwater drought analysis for Europe?
Inevitably, hydrogeological conditions and drought scales and definitions vary across Europe. GWL analysis and autocorrelation, perhaps with the aid of AI, could be developed. However, drought definition (scale of GWL drop), benchmark drought, and time/spatial scale should most likely be defined based on local/regional hydrogeological conditions.

Czechia

What is your definition of drought?
An amount of groundwater that is no longer able to cover human water consumption, water consumption for agriculture, ecosystems, etc. However, it very difficult define groundwater level limit or recharge/baseflow limit. According to my opinion, if groundwater levels are meeting their historically minimal value and still declining or reached such a low level that it caused some limitation (reduction in consumption) or damage to agriculture, ecosystems, etc.- this could be considered as a sign of drought.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?
No, we do not have a major drought. Groundwater levels reached a minimum around 2018 and they then rose. However, wells with the largest delay (3-4% of the total) have even been declining for the past 8 years and are currently reaching historic lows. This is a big difference from wells with

predominantly seasonal fluctuations and derived base flows that have been mostly increasing for the past three years. We are not able determine how big the problem is.

Are you currently interested in or undertaking national or sub-national drought analysis?
Yes, we do. The Czech Geological Survey is preparing a proposal for a methodology for evaluating different long-term fluctuations (last forty years) in ground water levels in different hydrogeological bodies (regions).

What time scales are of interest to you?
From the beginning of observation – 1960, monthly step.

What spatial aggregation do you use?
Most of all, it is area of hydrogeological zone (body).

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
Yes, we do. We distinguish wells depending on reaching a historical low as well. Shallow wells often hit all-time lows in 2018. However, some wells continued to decline in 2019 or into early 2021, and some are still declining today.

Do you consider droughts in multi-aquifer systems and, if so, how?
Yes, we do. We observe that deeper wells (or well from deeper aquifers) usually reach historical levels with a delay or are still falling today.

If you are already undertaking drought analysis, what methods are currently in use?
For now, we are following the path of identification (visual and partially automated) of various hydrographs of different types of level fluctuations in order to distinguish between the effects of natural dynamics, groundwater withdrawals, measurement errors and other influences and to select a representative types of fluctuation. We collect and have at our disposal all the principal driving forces - withdrawals, precipitation, infiltration, evapotranspiration, fluctuations in surface water levels, etc.

Have you encountered any analysis-related challenges?
We are trying to find out how to evaluate one relatively homogeneous hydrogeological body monitored by wells with predominant seasonal fluctuations, but also by wells that are without seasonal fluctuations and react to significant recharge episodes often with a delay of several years.

Are there additional methods you plan to use or would like to explore in the future?
We plan to use time series analysis with different types of drivers, clustering and, of course, trend analysis. Even if the trends for individual types of level fluctuations are often obvious, it is necessary to find the reasons (principal drivers) for changing trends in individual environments and for individual types of groundwater level fluctuations.

What are your ideas about the GSEU groundwater drought analysis for Europe?
The first steps are, of course, the visualization of all fluctuations in groundwater levels across Europe. We definitely recommend that any trend analysis should be conducted first on a selection of wells that can be considered reliable or representative and not affected by unexplained water management and measurement errors. This approach will certainly simplify and, above all, speed up familiarization with the behaviour of groundwater levels in different parts of Europe.

Denmark

What is your definition of drought?
We generally work with the overall concepts of four drought types: meteorological drought (M), hydrological drought (H), agricultural (ecological) drought (AE) and anthropogenic drought (A). Under the tree first concepts, we calculate several drought indices for drought monitoring in Denmark. They target the following variables: Precipitation (M), soil moisture (AE), streamflow (H), upper groundwater and deeper groundwater (H). Precipitation is based on data from the Danish Meteorological Institute

whereas the remaining ones are simulated with a spatially distributed, physically based hydrological model at national scale: The National Hydrological Model of Denmark (DK-model).

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?
For Denmark, the years 1995 to 1997 are considered the most severe drought during the last 30 years, characterized by a multi-year groundwater drought. Summer of 2018 was also severe. Larger drought events have also been reported in 1899, 1947, 1959, 1976, and in 1992.

Are you currently interested in or undertaking national or sub-national drought analysis?
Yes – we carry out national scale drought analysis. This is from a modelling perspective, but also how we can make better use of observations (streamflow, soil moisture, groundwater and vegetation) to monitor droughts and at the same time use these data to evaluate the model's capability to simulate drought occurrences. Previously, we have done a few catchment-based drought analysis studies both on historical and future climate model data.

What time scales are of interest to you?
Historical analysis of the last ~30 years, climate change impact analysis up until 2100, but also near-real time and seasonal forecasting.

What spatial aggregation do you use?
Hydrological model at 500 * 500 m and 100 * 100 m grid resolution. Simulation results may be aggregated to country or regional scale.

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
Yes, we are currently investigating temporal lags between the hydrological indices based on precipitation, soil moisture, streamflow upper groundwater and deeper groundwater.

Do you consider droughts in multi-aquifer systems and, if so, how?
Indices are calculated separately for upper and lower groundwater. The upper groundwater index relates to the uppermost water table (mostly relevant for agriculture, irrigation, infrastructure, groundwater dependent ecosystems), whereas the lower groundwater index relates to the piezometric head level in deeper aquifers (mostly relevant for water supply).

If you are already undertaking drought analysis, what methods are currently in use?
Hydrological indices as described above for 30-year simulation using DK-model. The indices are presented by Chan et al. (2021).

Have you encountered any analysis-related challenges?
Handling the anthropogenic drought concept, i.e., the responses from the society/human to the drought situations that may enhanced drought impacts. For instance, how to incorporate increased groundwater abstraction for water supply due to higher water demands under drought (no data is available on appropriate resolution). Determining thresholds for normal conditions in areas with high irrigation use.

What are your ideas about the GSEU groundwater drought analysis for Europe?
We would like to expand our investigation to other index types, also potentially combining remote sensing and modelling results.

Estonia

What is your definition of drought?
In Estonia, there is no national-level definition for drought. Currently, drought is defined according to the specific needs and objectives of each project.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?

In our region, significant drought events, referred to as "benchmark droughts," have been identified through previous research by our Latvian colleagues. They compared data from the Baltic states and pinpointed major drought events affecting all study sites during the periods of 1992–1994, 1996–1997, 2002–2004, and 2005–2007 (https://doi.org/10.1016/j.ejrh.2022.101049).

Are you currently interested in or undertaking national or sub-national drought analysis?
Currently, there is no previously conducted national drought analysis in Estonia. However, the Geological Survey of Estonia is actively involved in the LIFE-SIP AdaptEst project, in collaboration with the Estonian Ministry of Climate, the Estonian Environmental Agency, and Tallinn University. One of the work packages of this project focuses on mapping water bodies affected by climate change and developing mitigation measures. This includes plans to conduct drought analyses at both national and sub-national scales.

What time scales are of interest to you?
The time scales of interest for our drought analyses vary, depending on the specific requirements of each study. Spatial aggregation is also tailored to fit the needs of individual projects, ensuring that we can accurately capture the nuances of drought impacts across different regions.

If you are already undertaking drought analysis, what methods are currently in use?
In terms of methodology, we have examined autocorrelations in groundwater levels through various small-scale and nationwide projects. However, we have not yet conducted a detailed analysis regarding lags in droughts. Our methodologies are informed by the research conducted by our Latvian colleagues, who utilized several indices to calculate the components of drought events. These indices include the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Reconnaissance Drought Index (RDI), Standardized Groundwater level Index (SGI), and Standardized Sub-surface Runoff Index (SSRI). These tools have provided a robust framework for understanding the complex interactions between meteorological, hydrological, and groundwater data during drought events.

Have you encountered any analysis-related challenges?
One of the main challenges we face in our drought analysis is the presence of data gaps. These gaps need to be addressed before conducting thorough analyses. Additionally, some of our data series are too short to support comprehensive analyses, which limits our ability to draw long-term conclusions.

What are your ideas about the GSEU groundwater drought analysis for Europe?
Regarding the GSEU, we believe that a unified methodology incorporating seasonal analysis and the differentiation between shallow and deep aquifers would be beneficial. This approach would help create a more comprehensive understanding of drought impacts across Europe, facilitating better-informed decision-making and resource management strategies.

Finland

What is your definition of drought?
At Geological Survey of Finland, we do not have a specific definition of drought in relation to groundwater.

Do you have a major drought in your area that you use as ‘benchmark drought’ (and if yes, in which year)?
There is no major national drought benchmarked for our country.

Are you currently interested in or undertaking national or sub-national drought analysis?
Finnish Environmental Institute has carried out groundwater level monitoring since the early 1970s. This monitoring shows that the variation in groundwater levels is seen in 3–4-year cycles. Also the areas prone to drought are revealed. A time series analysis of monitoring is reported for the years 1975-1999. (Soveri et al. 2001)

Local droughts do occur, and Water Utilities using groundwater from smaller aquifers do encounter relevant risk of drought. In these cases, water intake may need to be adjusted during dry seasons. Finnish Environmental Institute (SYKE) has conducted a drought risk analysis on general level for the whole country. The aim is to analyse the risk of drought to agriculture, industry, and communities on current status. Also, Finnish Meteorological Institute has conducted a Wildfire Index concerning the fire sensitivity of the terrain. This index is based on modelling the dryness of the terrain.

Are there additional methods you plan to use or would like to explore in the future?

Related to the climate change and extreme weather events our main concern is rising water levels. A significant part of our water intake plants use bank infiltration to enhance their capacity and are thus situated near surface waterbodies. Currently we aim to find methods to monitor the water quality in order to predict the rise in water levels and to be able to prepare Water Utilities for possible flood risk.

France

What is your definition of drought?
Generally, we call "drought" below-normal GWL over quite a long period (seasonal to interannual).

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?
We rarely use major past droughts as benchmarks. However, sometimes, some comparisons with past major droughts are made after the events, but this is quite rare. In this case, the major drought used as a benchmark depends on the territory studied. We generally take the drought that led to the lowest measured GWL with the longest duration.

Are you currently interested in or undertaking national or sub-national drought analysis?
The drought analysis is undertaking at both scales: national or sub-national.

What time scales are of interest to you?
We are also interested in all time scales: the shortest GW droughts (with duration less than one year) or the longest ones (multi-year droughts).

What spatial aggregation do you use?
The analyses can be done for each GWL monitoring stations or aggregated to groundwater bodies. Sometimes, we use a subdivision of GW bodies that are based on GWL dynamics and were defined with clustering analysis. Indeed, according to the water table dynamic (led by physical parameters such as the nearness to the river, rock fracturation, so on), the propagation, the duration and intensity of the drought will be different.

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
We are of course looking for autocorrelation in GWL and propagation/lags in droughts, including how these parameters depend on low-frequency variabilities (Baulon et al., 2022b).

Do you consider droughts in multi-aquifer systems and, if so, how?
Of course, we also consider droughts in multi-aquifer systems either for unconfined or confined aquifers (e.g. multilayer aquifer of the Roussillon plain).

If you are already undertaking drought analysis, what methods are currently in use?
Different methodologies are used for undertaking drought analysis. Primarily, we use an indicator (Indicateur Piézométrique Standardisé – IPS; Vernoux and Seguin, 2013) which is very similar to the well-known SGI (Standardised Groundwater level Index; Bloomfield and Marchant, 2013) to determine the state of the water table and describe groundwater drought. Recently, we also developed "drought indicators" for local studies that can be also used on a larger scale such as (Manceau et al., 2020 ; Arnaud et al., 2023):

- The discharge speed without water input to illustrate groundwater resistance to rainfall deficit
- Indicator of groundwater sensitivity to rainfall
- Indicators based on periodogram or wavelet analysis to determine the system inertia and the response of the water table to meteorological drought
- Indicator to characterise the impact of groundwater droughts on surface hydrology
- While the IPS is more relevant for characterizing the state of the water table (and drought), these last indicators characterise more the aquifer vulnerability/resilience to drought.

Have you encountered any analysis-related challenges?
The main analysis-related challenges are about the use of probabilistic analysis for inertial water tables (with significant interannual variability), water tables with trends or even anthropogenic-influenced water tables.

Are there additional methods you plan to use or would like to explore in the future?
In future years, we plan to better characterise the impacts of groundwater droughts on aquatic environments and biodiversity.

What are your ideas about the GSEU groundwater drought analysis for Europe?
For GSEU groundwater drought analysis, it may be great to result in a map over Europe showing the sensitivity of aquifers to drought and on what time scale (short-term, long-term).

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Greece

What is your definition of drought?
Drought can be defined as water scarcity of water resources. It is characterised by reduced rainfall (below average trend). It affects both surface and groundwater systems.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?
Yes, 1989-1990 drought had a major impact in water resources in Greece. It was characteristic that many areas in Greece endangered to run out of potable water.

Are you currently interested in or undertaking national or sub-national drought analysis?
Yes.

What time scales are of interest to you?
Monthly, yearly (seasonal), and historical (for a 30-year period).

What spatial aggregation do you use?
Regional scale.

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
No.

Do you consider droughts in multi-aquifer systems and, if so, how?
No

Have you encountered any analysis-related challenges?
No.

Are there additional methods you plan to use or would like to explore in the future?
We are interested in exploring new methods.

Germany

What is your definition of drought?
A hydrological drought is characterized by low river discharge, connected to reduced groundwater levels, and soil moisture deficits affecting agriculture, ecosystems, and water supply. The German Weather Service (DWD) defines drought as a lack of water caused either too little precipitation and/or by greater evaporation (DWD 2022).

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?
The drought of 2003 is a benchmark drought due to its severity and widespread impact across Europe. In addition, 2018 and 2019 were years of dryness and extreme drought in most regions of Germany (DKKV).

Are you currently interested in or undertaking national or sub-national drought analysis?
We are interested in drought analyses at national scale to develop management strategies.

What time scales are of interest to you?
Short-term (seasonal to annual) and long-term (multi-year to decadal) scales

What spatial aggregation do you use?
Spatial aggregation ranging from local (single well) to regional (hydrogeological unit) and national scales.

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
We have not performed groundwater level autocorrelation analysis for drought purposes but mainly for clustering purposes.

Do you consider droughts in multi-aquifer systems and, if so, how?
No

If you are already undertaking drought analysis, what methods are currently in use?
The plan is to apply drought analysis at regional scale (Brandenburg & Lower Saxony). As a starting point, we would like to calculate the drought index. We have performed groundwater modelling to identify

areas where low groundwater levels might happen in the future due to climate change (Wunsch et al, 2022), although this study hasn't been done specifically for drought analysis.

Have you encountered any analysis-related challenges?
We would like to compute and incorporate the Standardized Groundwater level Index (SGI) as planned on the GSEU project. We would like to link this analysis to the respective groundwater system

What are your ideas about the GSEU groundwater drought analysis for Europe?
Analysis that allows identifying prone drought regions and possible cross-border impacts to propose jointly management strategies.

Hungary

Are you currently interested in or undertaking national or sub-national drought analysis?
We performed drought analysis only for specific regions in Hungary. The most exposed area for drought is the Great Hungarian Plain, especially in the SE region, the Danube-Tisza interflow, and the Nyírség region. The need and possibilities of irrigation were in the focus of these studies.

If you are already undertaking drought analysis, what methods are currently in use?
The NAGIS project aimed to develop a multipurpose geo-information system (National Adaptation Geo-information System) that can facilitate the policymaking, strategy-building and decision-making processes related to the impact assessment of climate change and founding necessary adaptation measures in Hungary https://nater.mbfsz.gov.hu/en/node/161). In the frame of this project two studies were prepared: 'Impact of climate change on shallow groundwater'; 'Vulnerability of drinking water supplying'. The reference interval was 1961–1990 and climate model projections were calculated for 2021–2050 and 2071–2100 periods. Detailed analysis of groundwater level time series was not performed.

What are your ideas about the GSEU groundwater drought analysis for Europe?
We are interested in drought analysis and expecting the contribution in development of a common method for groundwater drought analysis for Europe

Ireland

What is your definition of drought?
Ireland does not have a single consistent definition of drought. The three most commonly used definitions are:

- An Agricultural drought is "the shortage of precipitation during the growing season that impinges on agricultural activities leading to increased soil moisture deficits (SMD) that restricts growth". An SMD of over 75 mm indicates drought conditions.
- Climatological/Meteorological drought occurs when the amount of precipitation received in a specific area is considerably less than normal:
- A dry spell is a period of 15 or more consecutive days with less than 1 mm of rainfall.
- An absolute drought is a period of 15 or more consecutive days with less than 0.2 mm on each.
- A partial drought is a period of at least 29 consecutive days with a rainfall total averaging less than 0.2 mm of rain per day.
- Hydrological drought refers to reduced precipitation and/or increased evapotranspiration/evaporation amounts that primarily affects water supplies resulting in decreased reservoir, lake and ground water levels.
- There is no definition for groundwater drought

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?

There are a few historic benchmarks:

- The greatest drought is believed to have occurred from 1765 to 1768 with impacts across Britian and Ireland (Murphy et al. 2020).
- The driest year (i.e. lowest annual rainfall total) recorded in Ireland was 1887
- The "longest drought" occurred in 1938 where no rainfall occurred for 37 days.

More recently, the benchmark year in Ireland would typically be considered as summer 2018 which was one of the warmest and driest summers on record. Absolute drought conditions were recorded at 21 climatological stations.

Are you currently interested in or undertaking national or sub-national drought analysis?
Yes. Geological Survey Ireland is at the early stages of investigating groundwater drought across the country. We have commissioned a 4-year project (2023-2027) to monitor and model drought impacts as well as identify vulnerable/resilient aquifers.

What time scales are of interest to you?
Any timescale is of interest, though the longer scale droughts which are more likely to impact groundwater are of particular importance.

What spatial aggregation do you use?
Not defined as we have not produced any products yet.

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
Yes, this work has been carried out in projects that we have commissioned. We used autocorrelation as a proxy for groundwater memory to indicate drought susceptibility. Paper is available here: https://www.sciencedirect.com/science/article/pii/S0022169422008496

Do you consider droughts in multi-aquifer systems and, if so, how?
We have not carried out any work on this yet.

If you are already undertaking drought analysis, what methods are currently in use?
We have experimented with autocorrelation and "groundwater memory" methods to indicate susceptibility (paper linked above). We also intend to use SGI and Aquimod to assist in our characterisation and modelling of droughts.

Have you encountered any analysis-related challenges?
The main challenge is a lack of groundwater data. Consequently, we found it difficult to gather evidence of hydrogeological similarities across aquifer types.

Are there additional methods you plan to use or would like to explore in the future?
One method proposed by our consultants to be used in our 2023-2027 project is that of high and low pulse counts characterise the structure of time series with regards to the interannual variation. For more information on this method, see Heudorfer et al. (2019).

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Italy

Are you currently interested in or undertaking national or sub-national drought analysis?
The Geological Survey of Italy of ISPRA is not engaged in groundwater drought analysis. Another ISPRA Department is responsible for this matter.
In any case, drought effects on groundwater heads for Europe is an interesting challenge. Even if we do not have possibility to have active part in this topic, we are interested in joining as observers this matter within GSEU Project.

Malta

What is your definition of drought?
Droughts are a temporary decrease of the average water availability due for example to insufficient rainfall and are considered natural phenomena.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?
This depends on what is being understood as a benchmark drought. Over the last 10 years, Malta has been experiencing lower than average rainfall, which in a climate where the average rainfall is around 450 mm annually, anything below this benchmark is automatically considered as a drought. However, should one consider the dryest period in Malta, 2024 is looking to break the record with just 260 mm of rainfall. The dryest year before this was in 1961 with only 274 mm of rainfall.

Are you currently interested in or undertaking national or sub-national drought analysis?
Yes, the Energy and Water Agency is interested in undertaking a drought analysis at national level.

What time scales are of interest to you?
Annual

What spatial aggregation do you use?
National

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
No but we should

Do you consider droughts in multi-aquifer systems and, if so, how?
No

If you are already undertaking drought analysis, what methods are currently in use?
Application of SPI, RDI and drought index (on a national level)

Have you encountered any analysis-related challenges?
No

What are your ideas about the GSEU groundwater drought analysis for Europe?
In favour and would like to follow the process, plus contribute as necessary with Malta's data.

The Netherlands

What is your definition of drought?
Our definition of drought is Less water than normal.
A challenge in the application of this definition is the fact that normal is shifting e.g. due to the increasing variability of potential groundwater recharge (precipitation minus reference evaporation).
We regard it separate from water shortage, but this distinction is not always made which leads to confusion. Drought leads to less supply of water, but there only is water shortage when the supply is less than the demand.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?
The year 1976 is mentioned most. The Dutch national drought study from 2005 also mentions 2003, 1959, 1921 and 1911. More recently, reference is also made to 2018.
1996 was also dry but is never mentioned because it did not rain in the winter and did not lead to water shortage.

Are you currently interested in or undertaking national or sub-national drought analysis?
Yes

What time scales are of interest to you?
We regard a regime curve with monthly values as important reference. Such a regime curve consists of the 10th, 25th, 50th, 75th, and 90th percentile of all head values over a multiyear period. On the groundwater head viewer (https://www.grondwatertools.nl/gwsinbeeld/) we currently use simulations of time series models for a period of 20 years (the models have been of precipitation calibrated on the most recent 8 years so that they reflect the current situation) for this. We are working on criteria to determine the regime curves also based directly on measurements.

What spatial aggregation do you use?
We currently only work with piezometer data in the context of drought. However, within the GSEU-project we want to establish a set of monitoring wells that can provide a representative picture for the Netherlands.

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
Yes, e.g. through transfer-noise modelling of groundwater head time series with precipitation and reference evaporation as explaining variables (doi: 10.1111/gwat.12819).

Do you consider droughts in multi-aquifer systems and, if so, how?
We apply our analyses to all Dutch piezometers. Vertical head differences (between two piezometers in a single monitoring well) is a separate topic in the Groundwater head viewer.

If you are already undertaking drought analysis, what methods are currently in use?
We have used the Standardized Groundwater Index and investigated application of this using a variable distribution in time. We are also looking into separating natural (precipitation and evaporation) and anthropogenic (e.g. groundwater pumping) causes of drought.

Have you encountered any analysis-related challenges?
Yes, a good way to include the change of normal in evaluating drought. Also, the transfer-noise modelling needs to be improved for long time series and extreme situations (usually evaporation is energy limited in the Netherlands, but with higher temperatures and longer periods without precipitation there is a shift toward water limited evaporation.

Are there additional methods you plan to use or would like to explore in the future?
We hope to learn from our GSEU partners for this.

What are your ideas about the GSEU groundwater drought analysis for Europe?
Limit ourselves to analysis of measurement time series. Characterise series for all countries e.g. with (transient) SGI. It would be nice to put this in a pan-European paper similar to GeoERA-TACTIC (https://doi.org/10.1016/j.ejrh.2023.101399 and https://doi.org/10.1016/j.scitotenv.2022.153464).
Try to advance separation of natural and anthropogenic influences and translation into water availability and its variation in time.

Poland

What is your definition of drought?

Drought in groundwater – a periodic (not temporary) decrease in the location of the so-called "shallow" (not confined aquifer) below the adopted limit level, determined on the basis of long-term historical data. However, we speak of drought only when the scale of the phenomenon is greater than the local one, and its genesis is natural (or mainly natural).

Currently, in Poland, the limit state of the low water table is defined as the level of the water table calculated as the average of the minimum annual states of the water table position characterized by values lower than the value described as the average low level over many years.

It should be mentioned though, that in Poland there are different definitions in the country and sometimes drought is also discussed in the context of deeper aquifers. The definition quoted above is the one that has been used in recent years as part of the PGI-NRI forecasting task.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?
Rather not. On the scale of the last 40 years, there was a major drought in the years 1990-1992, but from 2015 onwards there was a period in which the extremes of 1992 are often exceeded.

Are you currently interested in or undertaking national or sub-national drought analysis?
Yes

What time scales are of interest to you?
Monthly and multi-annual

What spatial aggregation do you use?
The area of occurrence of low-pressure droughts is determined in an expert manner, taking into account the distribution of points with low-pressure and hydrogeological conditions, as well as historical ranges (frequency of occurrence) of other phases of drought (e.g. hydrological).

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
For many years, our predictions have been based on autocorrelation (exponential alignment). The method generally gave good results, but it was troublesome to choose the parameters manually (automatic approaches did not give satisfactory results in this respect) – we made many scenarios for a given point – we chose two extreme ones – it happened that despite many different parameter settings, we got similar results, and it was difficult to differentiate the scenarios.

Autocorrelation is very strong in groundwater, and it is worth using it, but for us it has not always worked very well in the adopted method (exponential alignment) for differentiating forecasting scenarios.

Do you consider droughts in multi-aquifer systems and, if so, how?
Not at the moment. But for many years we have been studying low levels at different water bearing horizons – we have divided our observation points into groups depending on the depth to the aquifer top. Currently, we do such analyses sporadically, not cyclically.

If you are already undertaking drought analysis, what methods are currently in use?
For seasonal forecasts, we currently use our own simple method based on the curves of rising and falling the water table determined from long-term data and determining their probability of occurrence. Due to the provisions of the regulations in force in our country, we wanted to build two extreme forecasting scenarios, which is why we currently use this method.

Have you encountered any analysis-related challenges?
Long-term forecasts are a challenge for us. Recently, inspired by the approaches presented by the group, mainly from France and Germany, we have developed a model using MDTWP for low-frequency diagnostics and predictions. However, when it comes to forecasts – there is still a lot of work to be done – these forecasts only show a general trend of change – based on low frequencies. Previously, we only

used the regression curve for this type of analysis, calculated only over relatively long long-term observation sequences.

Are there additional methods you plan to use or would like to explore in the future?
In the future, when we automate our measurements across the entire monitoring network, we want to include precipitation and/or satellite data in forecasts in order to, for example, better determine the probability of a given scenario coming true.

What are your ideas about the GSEU groundwater drought analysis for Europe?
It's hard to say. Maybe after this survey, the goals will become more clear – at least in terms of the time step – the timeframe of the forecast or which groundwater levels the forecast is supposed to refer to – only the shallowest one or deeper? – then it will be easier to answer something.

Romania

What is your definition of drought?
Drought is a complex phenomenon that occurs due to lack of rainfall and reduced soil moisture supply, with negative effects on plants, aquatic areas and society as a whole. In general, the duration of drought can be different depending on the approach: e.g. lack of rainfall for 1-3 months (meteorological drought) can cause a pedological or agronomic drought of 2-4 months and reduce runoff over a period of 4-6 months (hydrological drought), and aquifers can be affected even after a year (do O, 2005).

In Romania and other countries, two types of rainfall deficit situations have been defined: dryness and drought periods. A dry period is an interval of at least 5 consecutive days in which no precipitation has fallen, or precipitation has not exceeded the multiannual daily average. A drought period consists of at least 14 consecutive days in the cold half of the year (October to March) and at least 10 consecutive days in the warm half of the year (April to September) when no precipitation has fallen or, if precipitation has fallen, it has not exceeded 0.1 mm.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?
In 2011, the end of summer and the beginning of autumn brought the longest and most widespread drought in Romania this century, being almost two months without rain. Also years: 2000, 2011, 2018, 2019, 2022.

Are you currently interested in or undertaking national or sub-national drought analysis?
We are very interested.

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
Not currently, but it is a good method in the case of studying the drought phenomenon.

Do you consider droughts in multi-aquifer systems and, if so, how?
In a multi-layered system, drought could be highlighted by statistical methods.

If you are already undertaking drought analysis, what methods are currently in use?
We did not have this occasion by now, in our institute.

Are there additional methods you plan to use or would like to explore in the future?
Statistical analysis.

What are your ideas about the GSEU groundwater drought analysis for Europe?
Romania is a data contributor to EU databases on drought (see links in references). IGR is not the authority responsible for the management of the Hydrogeological database. That is why IGR did not have as main interest groundwater drought analysis. But the project GSEU is the best occasion to introduce in Romania new methods of analysis regarding the impact of drought on underground water.

References and additional information:

Alfonso do Ó., 2005, Regional drought analysis and mitigation using the SPI, Proceedings of 21st ICID Conference, Topic 4. 15-19 May 2005, Frankfurt-Słubice, Germany-Poland, CD-ROM

https://drought.emergency.copernicus.eu/tumbo/edo/map/

https://water.europa.eu/freshwater/europe-freshwater/freshwater-themes/drought/near-real-time-map-viewer-2013-ecosystems-exposed-to-drought-conditions-in-europe

Serbia

What is your definition of drought?
We characterize drought as water deficit (both surface and groundwater) in relation to normal conditions which is highly related to weather conditions/periods.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?
Yes, Vojvodina area in Northern Serbia (Pannonian Basin) is the are most affected with drought. Remarkable years were 2000, 2012, 2017 and 2021. 2007 was memorable for the heat wave and very hot summer. Research done in Vojvodina shows that drought damage ranges are depending on: soil characteristics, groundwater level, crop and hybrid type, total precipitation deficiency, precipitation coverage and other factors (temperature etc.).

What time scales are of interest to you?
Monthly, yearly (seasonal), and historical (for a 30 year period).

What spatial aggregation do you use?
Regional scale.

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
Yes - temporal lags, taking into account precipitation, temperature, groundwater, and surface water of an area.

Do you consider droughts in multi-aquifer systems and, if so, how?
No.

If you are already undertaking drought analysis, what methods are currently in use?
We look at the correlation between groundwater and drought through groundwater regimes and groundwater balance.

Have you encountered any analysis-related challenges?
No.

Slovakia

If you are already undertaking drought analysis, what methods are currently in use?
Concerning current practices in drought analyses, there is a wide spectrum of methods, attitudes and benchmarks used in Slovakia. They were already summarised in a book monograph by Fendeková & Ženišová eds., 2010 (Fendeková, M., Ženišová, Z., Demeterová, B. Fendek, M., Fľaková, R., Gavurník, J., Krčmář, D., Macura, V., Némethy, P., Slivová, V., 2010: Hydrogeologické sucho [Hydrogeological drought; in Slovak]. Eds. Fendeková, M., Ženišová, Z.; SAH Publishers, Bratislava, , AH 15,02, ISBN 978-80-969342-7-0; 190 pp.). The aim of the monograph is to demonstrate the current state of knowledge of the phenomenon of drought, to propose a methodology for its assessment in the underground component of the hydrosphere and to apply new methodological procedures in the pilot area (Upper Torysa river basin).

The book is divided into four main chapters, in which the attention is successively paid to the current state of knowledge of the drought phenomenon (chap. 1), background and methods of hydrogeological drought assessment (chap. 2), a case study of hydrogeological drought assessment in the Upper Torysa catchment (chap. 3) and the impact of hydrogeological drought on water recharge in the Upper Torysa catchment (chap. 4). The authors of the monograph are affiliated to Department of Hydrogeology, Faculty of Natural Sciences, Comenius University Bratislava (M. Fendeková, Z. Ženišová, M. Fendek, R. Fľaková, D. Krčmář and P. Némethy), Department of Water Management of Landscape of the Faculty of Civil Engineering of the Slovak University of Technology in Bratislava (V. Macura) and the Slovak Hydrometeorological Institute (B. Demeterová, J. Gavurník, P. Škoda and V. Slivová).

Slovenia

What is your definition of drought?
The Slovenian Environmental Agency (ARSO) defines groundwater drought as a period of water deficit in an aquifer or a group of aquifers compared to normal conditions (Sheffield and Wood, 2011). They use the groundwater drought indicator in intergranular aquifers based on the assessment of the intensity and spatial distribution of the monthly standardized groundwater level index (SGI) for individual years. They analyse 31 monitoring sites selected according to the length of observations, the representativeness of the natural fluctuation of groundwater levels without artificial influences, the spatial representativeness of the site and the technical suitability of the monitoring site.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?
No, we are not aware of anyone using benchmark drought for analysis.

Are you currently interested in or undertaking national or sub-national drought analysis?
No, official national groundwater drought analyses are currently carried out annually by the Slovenian Environmental Agency. The analyses are presented on the internet (SGI data).

What time scales are of interest to you?
Monthly or annual.

What spatial aggregation do you use?
The Slovenian Environmental Agency analyse data based on our main intergranular groundwater bodies. At GeoZS we did some analyses on smaller areas.

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
No.

Do you consider droughts in multi-aquifer systems and, if so, how?
No.

If you are already undertaking drought analysis, what methods are currently in use?
At GeoZS we did some analyses on smaller areas, using method based on ranking statistics defined by lower percentiles indicating low groundwater levels or vice versa. Another method that we have also used in the past is based on the univariate Standardized Groundwater Index – SGI.

Have you encountered any analysis-related challenges?
One of the challenges was the lack of longer time series of groundwater levels (more than 30 years) and the non-uniform spatial distribution of the observation stations in the past. Another challenge with long time series are anthropogenically altered groundwater levels. In our study, we omitted monitoring sites with anthropogenic changes.

Another problem that could not be solved in the analysis was the general statistical linear trend of the decline in the groundwater levels, which affects the varying intensity and size of the deficit of the dry periods. Due to the occurrence of a linear trend, there have been a large number of droughts in recent times. The linear trend in groundwater level fluctuations is largely the result of anthropogenic activities (construction of hydropower plants, creation of accumulation lakes, regulation of rivers and streams for irrigation purposes, etc.) and also climatic factors.

What are your ideas about the GSEU groundwater drought analysis for Europe?
From a Slovenian perspective, we suggest as a first step to calculate the annual SGI index for the first/upper aquifers to get an overall picture and then decide how to further evaluate the data more precisely (include multilayers or monthly data).

Spain (IGME)

What is your definition of drought?
A simple definition is to consider it as a water deficit in relation to normal conditions. Depending on the nature of the water deficit, droughts can be categorized into four types: meteorological, hydrological, agricultural, and socioeconomic. If we focus on groundwater, we should use groundwater levels to assess the water deficit in relation to normal conditions.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?
The worst recent droughts in Spain were produced in 1991 - 1995, 2016 - 2017 and the current drought (2021-nowadays). The severity also depends on the área. For example, in Catalunya the 2021-2024 drought has been the more severe one.

Are you currently interested in or undertaking national or sub-national drought analysis?
Yes, we are interested.

What time scales are of interest to you?
We are currently interested in the analyses at different scales (country scale, basins, aquifers, alpine mountain ranges).

What spatial aggregation do you use?
We have work at different scale. For example, in the basin scale analyses we apply a preliminary cluster analysis to identify homogeneous hydro-climatic areas, which are used as unit to perform the analyses of drought propagation. Gómez-Gómez, Juan de Dios & Pulido Velazquez, David & Collados Lara, Antonio-Juan & Chacón, Francisca. (2022). The impact of climate change scenarios on droughts and their propagation in an arid Mediterranean basin. A useful approach for planning adaptation strategies. Science of The Total Environment. 153128. 10.1016/j.scitotenv.2022.153128.

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
Yes, we look at the propagation and lags in droughts. See for example:
Gómez-Gómez, Juan de Dios & Pulido Velazquez, David & Collados Lara, Antonio-Juan & Chacón, Francisca. (2022). The impact of climate change scenarios on droughts and their propagation in an arid Mediterranean basin. A useful approach for planning adaptation strategies. Science of The Total Environment. 153128. 10.1016/j.scitotenv.2022.153128.

Do you consider droughts in multi-aquifer systems and, if so, how?
We have mainly worked at basin scale. I guess that a preliminary cluster analysis should be applied, as we do to identify the spatial resolution for the analyses at basin scale.

If you are already undertaking drought analysis, what methods are currently in use?
We use the SPI index, and we apply its definition to different variables depending on the type of drought analysed. Using the same mathematical/statistical definition of drought allow us to perform and analyses of the propagation and lags of droughts.

Have you encountered any analysis-related challenges?

No.

Are there additional methods you plan to use or would like to explore in the future?
We are open to apply different approaches.

What are your ideas about the GSEU groundwater drought analysis for Europe?
We can generate a very interesting product, with a lot of potential impact on the visibility of groundwater.

Sweden

What is your definition of drought?
At SGU we do not use any strict definition or calculation of groundwater drought. Instead, we focus on groundwater levels and have a semi-automatic system where we analyse the risk of consequences due to low groundwater levels. In practice, the relative groundwater level (in terms of percentiles) is calculated automatically with model for areas of 4x4 km. If the groundwater level is low at the present and/or will probably be low during the next couple of months we can decide to announce an official message of "risk for water shortage due to low groundwater levels" for a specific county. Besides modelled groundwater levels, other estimated factors such as hydrogeological conditions, dependency of groundwater and previous experiences of consequences in the area in question are included in the assessment. This implies that an announcement could be made for some areas when the groundwater level is at the 15th-percentile but not for other areas even if the levels is as low as the 5th-percentile. Drought analysis is not carried out for individual sites or groundwater bodies. Instead, the analysis is performed on a regional scale. The time scale of interest for drought in Sweden is often less than a year, since many of the aquifers in Sweden react rather quickly to changes in weather and the winter often results in significant groundwater recharge. For climate modelling purposes we have used a definition that a period of groundwater drought is present if the potential groundwater recharge is less than 10 mm during the last 30 days. Potential groundwater recharge is in this case given by modelling of water balance in an open aquifer consisting of glacial till in a permanent recharge area. However, we have not used this definition in continuous monitoring or evaluation of present drought periods.

What are your ideas about the GSEU groundwater drought analysis for Europe?
It could be beneficial to have a common method to calculate groundwater drought, such as SGI, in a European scale. However, I think it must be very clear that it is not directly linked to consequences since the hydrogeological conditions and the dependency of groundwater is very variable throughout Europe. So far, we have not been able to objectively include consequences for Swedish conditions despite that we are several colleagues with decades of experience within the topic.

United Kingdom

What is your definition of drought?
Using SGI (by analogy with SPI), groundwater droughts of varying intensity have been defined by UK researchers as periods where SGI for an observation borehole is below a given value of SGI, e.g SGI ≤ -2 corresponding to extreme GW drought, $-1.5 \geq$ SGI > -2 corresponding to severe drought, $-1.0 \geq$ SGI > -1.5 corresponding to moderate groundwater drought, $0 \geq$ SGI > -1 corresponding to minor groundwater drought and SPI > 0 corresponding to no groundwater drought. Notwithstanding this, monthly reporting of groundwater status, including groundwater drought, for the UK are reported as one of seven 'traffic light' classes as monthly rank for the period of record for a given site. The classes being: Exceptionally high, notably high, above normal, below normal, notably low, and exceptionally low groundwater levels. See https://nrfa.ceh.ac.uk/monthly-hydrological-summary-uk . Or, in the case of the 1-, 3- and 12-month groundwater level forecast for the UK, as one of seven percentile range classes, e.g. >95, 87-95, 72-87, 28-72, 12-28, 5-12, and <5%tiles. See https://hydoutuk.net/.

Do you have a major drought in your area that you use as 'benchmark drought' (and if yes, in which year)?

For GW droughts: 1975-76, 1988-93,1995-98, 2004-2006, 2010-2012. See also description of major episodes of drought in the UK at https://www.ceh.ac.uk/our-science/projects/drought-inventory.

Are you currently interested in or undertaking national or sub-national drought analysis?
National, regional and aquifer specific

What time scales are of interest to you?
From 1 to 12 months for current status and forecast summaries, to multi-annual to understand large-scale drought dynamics and propagation, to multi-decadal to understand the effect of longer-term climate variability on drought histories, to centennial for groundwater drought modelling under climate change

What spatial aggregation do you use?
None. Although once drought histories have been established for multiple sites, cluster analysis will be used at the regional, national and continental scales to understand drought dynamics across these scales.

Do you look at autocorrelations in groundwater levels and propagation and lags in droughts?
Yes, to understand the relationship with driving climatology and the effect of aquifer and catchment characteristics on system memory and response to meteorological droughts.

Do you consider droughts in multi-aquifer systems and, if so, how?
Some limited work on semi-confined / confined aquifer response to drought but generally most UK aquifers that are used are unconfined hence there is limited work on confined aquifers.

If you are already undertaking drought analysis, what methods are currently in use?
Modelling individual GW level hydrographs using Marchant et al., (2022), estimating SGI time series and extracting droughts for analysis and characterisation using Bloomfield & Marchant (2013).

Have you encountered any analysis-related challenges?
Obtaining suitable long, high quality GW hydrographs. Short records. Changes in monitoring frequency. Obtaining suitable site-specific metadata related to aquifer, catchment characteristics to understand aquifer and catchment controls on GW response to meteorological droughts. Obtaining information related to water resource management practices that may influence observations of groundwater drought and their analysis.

Are there additional methods you plan to use or would like to explore in the future?
Joint SPI, SSI, SGI analysis across the UK. Analysis of recession characteristics to inform our understanding of GW drought dynamics.

What are your ideas about the GSEU groundwater drought analysis for Europe?
We should produce a couple of outputs. First a simple 'live' status map similar to the one used in BGS' Hydrological Summary for any sites with live data updated on a monthly or quarterly basis. This could include status of any site with say 5 years or more of data and would be coded by monthly rank (for example as one of seven percentile classes). The second approach would be SGI-based on sites with more data (say ~20 years or better of data). This would be a map of SGI status that can be queried for any given date over that period (monthly time-step).

13. Annex V – National Approaches to Groundwater Level Trend Detection and Quantification

Austria

Are you currently interested in or undertaking national trend analysis of groundwater heads? What time scale (e.g., recent over-abstraction/recovery, long-term trends) are of interest to you? What spatial aggregation do you use? How do you treat multi-aquifer systems? If you are already using trend analysis, what methods are currently in use? Have you encountered any particular analysis-related challenges? Are there additional methods you plan to use or would like to explore in the future?

Long-term trend analyses are often carried out using publicly available data from the national groundwater monitoring network. The Austrian Hydrographic Service provides verified groundwater level data on a monthly basis (aggregated values), but it is also possible to obtain raw data at a higher temporal resolution, e.g. on a daily basis. Data series with a minimum duration of 30 years should be considered for long-term trend analyses in order to reduce the influence of outliers. This criterion is also important for the analysis of meteorological data (precipitation, air temperature and evapotranspiration). However, 30-year time series are not available for a relatively large number of monitored wells and even less for springs. It is usually necessary to compare the long-term trends of several groundwater monitoring sites and it is difficult to choose an appropriate time frame when the length of the data series varies considerably and if there are also data gaps. The challenge is therefore either to exclude groundwater monitoring sites or to shorten the time period. A commonly used method is the Mann-Kendall Test (MK) or Seasonal Mann-Kendall Test (SK) to assess whether there is a monotonic upward or downward trend of the variable over time, in combination with a Theil-Sen (TS) estimator.

Additional Information

Haas, J.C. & Birk, S. (2019): Trends in Austrian groundwater – Climate or human impact? Journal of Hydrology: Regional Studies, 22, 100597. https://doi.org/10.1016/j.ejrh.2019.100597

Federal Ministry Republic of Austria – Agriculture, Forestry, Regions and Water Management (2023): Austria's Water Treasure - Protecting and using our groundwater sustainably, 23 pp., Vienna, Austria. https://info.bml.gv.at/service/publikationen/wasser/austrias-water-treasure---protecting-and-using-our-groundwater-sustainably.html

Kralik, M., Benischke, R., Wyhlidal, S. & Philippitsch, R. (2017): First Water-Isotope-Map (δ18O, δ2H, 3H) of Austria: Applications, Extremes and Trends. Procedia Earth and Planetary Science, 17, 924-927, https://doi.org/10.1016/j.proeps.2017.01.021.

Schartner, Ch. & Kralik, M. (2011): Trends der Grundwassertemperatur. REP-0328, 28 S., Umweltbundesamt, Vienna, Austria. https://www.umweltbundesamt.at/fileadmin/site/publikationen/REP0328.pdf

What are your ideas about trend analysis of groundwater heads for Europe?

Besides the challenges mentioned above it would be important to cluster the monitoring points based on the long-term trend analysis, the hydrogeological setting of aquifer types and the meteorological conditions (monitored data and RCP scenario data).

Belgium-Flanders

Overview

For the Flanders Region in Belgium trend analysis on groundwater heads is carried out by Flanders Environment Agency (VMM). VMM manages different monitoring networks, among which:

Monitoring Network 1:

- Ca. 550 monitoring stations with in total ca. 900 screens
- Monthly manual measurements.
- Currently (2022-2026) a project is being carried out to equip 700 screens at 440 locations with loggers and telemetry in order to get near-real time high frequency timeseries of groundwater heads
- Uniformly distributed across different aquifers (phreatic and confined)
- As much as possible outside (direct) anthropogenic influence

Monitoring Network 8:

- Around 2200 monitoring stations with in total around 5400 screens
- Bi-annual manual measurements
- Phreatic aquifers in agricultural and natural areas
- Indicator network:
- Consists of 154 phreatic screens from monitoring network 1 with calibrated SWAP models
- Used for monitoring and prediction of drought/wet conditions

Methods
Trends are assessed at the individual screen level using the "Trendanalist 6" software (see https://www.amo-nl.com/software/trendanalist/, in Dutch). Trendanalist determines a linear trend in the time series and selects a suitable significance test based on its characteristics taking into account non-normal probability distribution, seasonal effects, autocorrelation, missing and censored values. The program's internal expert system makes a choice for each dataset from various linear models with season and noise modeling, and various forms of the Mann-Kendall test. These forms vary concerning the handling of seasonal effects and/or autocorrelation.
To gain insight into the proportions of natural and anthropogenic variations in the trends we use the indicator network where physically based models (SWAP; Kroes et al. 2017) are fitted to the time series. The SWAP models incorporate climatic effects on the groundwater level but ignore management-induced impacts such as groundwater abstraction. According to Heuvelmans et al. (2011) the management-induced contribution to observed trends in groundwater levels can therefore be derived by analysing trends in the model residuals. Trends on the simulated groundwater levels and the model residuals are calculated using the statistical program Trendanalist 6. Anthropogenic influence is only detected on individual trends at the screen level.
For confined groundwater a statistical approach is used. The confined head time series are pre-processed to fill gaps and remove outliers in the time series (combination of LOESS, SARIMAX, Kalman, ARIMA, and correlations depending on data availability). Finally, trend breaks and trendlines for the different segments are derived based on reliable time series without gaps.

Visualisation
Trends are determined for long term (2000 to the current year) or short term periods (6-years e.g. 2016-2022 ~Water Framework Directive). Trends are classified (0-0.05 m/yr = weak decline/increase; 0.05-0.1 m/yr = moderate decline/increase; >0.1 m/yr = strong decline/increase; >0.5 m/yr: very strong decline/increase). Bar plots of percentages over the different classes, and maps with trend classes per well screen are presented for Flanders. A distinction is made between phreatic and confined aquifers.

Conclusions on the groundwater body level in River Basin Management Plans (WFD) are made based on percentage thresholds for declining trends.

Challenges
VMM is looking forward to improve the ability to detect trend breaks and trend reversals in both phreatic and confined aquifers, to aggregate identified trends at e.g. the ground water body level, and to better differentiate between climatic and anthropogenic impacts on the trends in the groundwater level time series.

References
https://www.vmm.be/water/grondwater/grondwaterstand (in Dutch)
https://sgbp.integraalwaterbeleid.be/grondwatersysteem (groundwater system-specific parts of the River Basin Management Plans, in Dutch)
Trendanalyst website: https://www.amo-nl.com/software/trendanalist/
Kroes JG, JC Van Dam, RP Bartholomeaus, P Groenendijk, M Heinen, RFA Hendriks, HM Mulder, I Supit, PEV vanWalsum, 2017). SWAP version 4; Theory description and user manual. Wa-geningen Environmental Research, Report 2780.
Heuvelmans G, A Louwyck, J Lermytte, 2011. Distinguishing between management-induced and climatic trends in phreatic groundwater levels. Journal of Hydrology, 411. https://doi.org/10.1016/j.jhydrol.2011.09.039
https://repository.europe-geology.eu/egdidocs/resource/geoera+resource+deliverable+d35+3d+visualization.pdf

Croatia
Overview of current practices and needs
HGI-CGS is not presently engaged in national-scale groundwater heads trend analysis.
Over the previous years, HGI-CGS has been contracted for different tasks, including trend analysis of groundwater levels in major porous aquifers found in the Pannonian basin in northern Croatia. The tasks have been mostly related to the implementation of WFD. Linear regression has been used for trend analysis of groundwater levels in major aquifer systems in the Drava and Sava river basins. The aquifers are mostly unconfined or semi-confined.
However, HGI-CGS is no longer responsible for this or a similar task.

Cyprus
We are currently reviewing groundwater levels from ~80 telemetric data loggers covering the main water bodies, on an annual basis. The main focus is on aquifer dynamics and groundwater recharge and in trying to discern whether the latter is within expected averages.

In terms of trend analysis, a rather descriptive and simplified method is used. The daily values are converted into monthly averages and a status (increase, decrease or no change) is reported for each station, based on the water levels at the beginning and the end of the hydrological year. A general descriptive trend is reported for each groundwater body based on the status of the stations.

A more scientific method, looking both at the yearly and the long-term trends is of interest to us. In a semi-arid environment as such of the eastern Mediterranean, both yearly recharge and long-term trends are very important in groundwater management and protection.

Adapting a common scientific method, looking both at the short-term and the long-term trends, is of interest to us.

Czechia

Groundwater resources are estimated in Czech Republic through base flow at a monthly time step. The Czech Geological Survey is not involved in this assessment. However, fluctuations of groundwater levels at wells are not fully used in the Czech Republic to assess groundwater resources in the hydrogeological bodies. The big problem is in the interpretation of the behaviour of groundwater levels.

The current effort is to evaluate the hydrogeological body as a whole for whole area of Czech Republic. However, in one hydrogeological body (even in the bodies with little influence of withdrawals) one can find wells with predominant seasonal fluctuations but also wells that are without seasonal fluctuations and react to significant recharge episodes often with a delay of several years. Wells with the largest delay (3-4% of the total) have even been declining for the past 8 years and are currently reaching historic lows. This is a big difference from wells with predominantly seasonal fluctuations and derived base flows that have been mostly increasing for the past three years. It is very likely related to the existence of a multi-aquifer system, whose individual aquifers can be differentiated (and at the same time assigned to upper and deeper hydrogeological bodies), but also the definition of some individual aquifers is still undetermined in many areas. The Czech Geological Survey is preparing a proposal for a methodology for evaluating different long-term fluctuations (last forty years) in ground water levels in different hydrogeological bodies (regions).

For now, we are following the path of identification (visual and partially automated) of various hygrograms of different types of level fluctuations in order to distinguish between the effects of natural dynamics, groundwater withdrawals, measurement errors and other influences and to select a representative type of fluctuation. We collect and have at our disposal all the principal driving forces - withdrawals, precipitation, infiltration, evapotranspiration, fluctuations in surface water levels, etc.
We plan to use time series analysis with different types of drivers, clustering and, of course, trend analysis. Even if the trends for individual types of level fluctuations are often obvious, it is necessary to find the reasons (principal drivers) for changing trends in individual environments and for individual types of groundwater level fluctuations.

Can you highlight any additional information such as publications, reports, or web links related to the methods you are currently employing or wish to use in the future?
The Czech Geological Survey is not involved in ground water assessment so far. Current approach for ground water level assessment is available e.g. on https://hamr.chmi.cz/pozemni-2023-47.

What are your ideas about trend analysis of groundwater heads for Europe?
The first steps are, of course, the visualization of all fluctuations in groundwater levels across Europe. We definitely recommend that any trend analysis should be conducted first on a selection of wells that can be considered reliable or representative and not affected by unexplained water management and measurement errors. This approach will certainly simplify and, above all, speed up familiarization with the behaviour of groundwater levels in different parts of Europe.

Denmark

At GEUS, groundwater trend analysis has been mainly carried out through modelling. The GEUS developed and operated national hydrological model (DK-Model) has been employed during several iterations of national scale climate change impact analysis using ensembles of climate models (Siedenfaden et al., 2022). The climate change impact has been calculated as the difference in specific statistical parameters of simulated groundwater level (mean, q1, q99, exceedance probabilities, etc.) between the historical reference run and the impact simulations. These analyses resulted in spatially distributed knowledge (gridsize of 500 * 500 m) on trends in groundwater level dynamics and related uncertainties, defined as precision across the ensemble of climate models. The results of a very recent project on climate change impact analysis were made publicly available via https://hipdata.dk/ (Figure 1). With the help of the DK-Model groundwater drought indices were calculated and analysed to better investigate extreme events.

Examples of climate change impact can be seen on the water table depth viewer: https://hipdata.dk/.
From an observational perspective, real-time data from wells with automatic loggers are shown with respect to the well-based statistics, calculated as quantiles of the distribution of the entire timeseries of a given well. Certain quantiles have been categorized, ranging from high to low water table depth. The real-time data and the statistics are available via: https://grundvandsstanden.dk/ (Figure 2). The quantiles are calculated based on monthly and seasonal data and the user can choose which one to visualize. This may not be a stringent trend analysis, but it allows for a straightforward evaluation of the current groundwater level and a visual assessment if it is above or below what is normal for a given month or season.

Example of observed groundwater levels can be seen on the viewer: grundvandstanden.dk. With the modelling work GEUS has mainly focused on long-term trends, near future (2041-2070) and far future (2071-2100) while the observational analysis is more focused on the current conditions.
Our current projects focus on forecasting of hydrological variables from 2-day to seasonal time scales using ensembles of weather models. The forecasting will include simulations of groundwater level and spatially distributed results will be made available to users. The format and processing of the forecasted groundwater level is yet to be decided.
Both, modelling and observational based analysis take multi-aquifer systems into consideration, but much attention (especially the observational network) is given to the shallow groundwater system.
With our current systems, we are mostly investigating the groundwater level trend as a result of changes in precipitation and temperature. Changes in abstractions, water demands and land use are currently not considered, but need to be included for a holistic assessment.
Contact: Julian Koch (juko@geus.dk)

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Estonia
Geological Survey of Estonia have been actively engaged in national-scale groundwater head trend analysis for groundwater bodies (GWB) status assessment (period 2014-2019, otherwise overseen by the Estonian Environmental Agency), with groundwater level trends being one component of Test 9. However, our utilization of trend analysis primarily occurs during local studies to assess the impact of activities such as quarrying/mining or other groundwater consumption on aquifers. The focus is on evaluating the trends in specific areas rather than conducting an overarching national groundwater trend analysis. Regarding the time scale of interest, we are open to examining trends across all time frames,

whether it involves recent over-abstraction and recovery or long-term patterns. This flexibility allows us to address various concerns related to groundwater dynamics, offering a comprehensive understanding of temporal trends. In terms of spatial aggregation, the groundwater level trend analysis is carried out on a per-GWB basis during the assessment of groundwater bodies. Each monitoring well within a given GWB undergoes trend analysis, followed by an evaluation of whether the trends in water level rise or fall exceed 20% of the GWB's surface area. This is determined by employing spatial analysis of monitoring well locations, utilizing the Thiessen polygon method to delineate influence areas of each monitoring well. When dealing with multi-aquifer systems, we conduct separate trend analyses for each aquifer layer based on the screen location of each well. This approach ensures that the unique characteristics of each aquifer are considered, providing a more nuanced understanding of groundwater trends within complex systems. Currently, our trend analysis relies on linear regression as the primary method. However, we acknowledge certain challenges, such as temporal gaps in the data and the lack of consistency in the monitoring network. Addressing these challenges is crucial for enhancing the reliability of our analyses.

Finland

Are you currently interested in or undertaking national trend analysis of groundwater heads?
We are interested in the long-term trend analysis of groundwater heads and hope to gain more knowledge and experience on this topic. We aim to develop the use of our existing data resources, and in this, trend analysis could provide further insight into the data.

There are some sites in Finland that have groundwater level data since 1969 (measurements 2-4 times/year). There are also sites with data between 1969-2017, but where monitoring has since been discontinued. On top of these, we have 4-8 NRT monitoring stations that have been operational since 2021. At the NRT sites, data is collected from 2-6 monitoring wells.

What time scale (e.g., recent over-abstraction/recovery, long-term trends) are of interest to you?
We are mainly interested in analysis of long-term trends.

Can you highlight any additional information such as publications, reports, or web links related to the methods you are currently employing or wish to use in the future?
Public Finnish groundwater data has been used in some research dealing with long-term trend analysis. See for example Nygren, M., Giese, M., & Barthel, R. (2021). Recent trends in hydroclimate and groundwater levels in a region with seasonal frost cover. Journal of Hydrology, 602, 126732.

France

We are currently undertaking trend analysis in different studies. Generally, these studies are done at a local scale where trend analysis is not an end in itself. It is often part of a set of statistical tests intended to answer a specific question in a given territory. These questions are very diverse. At a national scale, the latest study dates back 2021 aiming to identify long-term trends that may be linked to climate change. Either at the national or local scales, several time scales (short- and long-term) can be studied depending on the study objectives. In terms of objectives, they are very various (e.g., identify and quantify recent over-abstraction, quantify long-term trends linked to abstraction or climate change). Both the shallowest and deepest aquifers can be studied in these studies.

From a methodological perspective, trend analysis is generally conducted on annual variables (maximum, minimum, averages) over the longest period as possible. At a local scale, the period may be however quite short whether the study objective is to highlight a particular phenomenon (e.g. over-abstraction over a given period). Sometimes, even at the national scale, trend analysis is conducted over a short period such as for state of play within the water framework directive (12-yr period).

Before carrying out trend analysis, the autocorrelation in the time series is calculated. This will guide the choice of trend test. Indeed, in case of significant autocorrelation a modified Mann-Kendall trend test (Hamed and Rao, 1998) will be used for trend analysis, while if there is no significant autocorrelation a "classical" Mann-Kendall trend test (Kendall and Stuart, 1976) will be used. The Mann-Kendall trend test, whether or not suitable for a time series with significant autocorrelation, is used for testing the statistical significance of the trend, while the Sen's slope (Sen, 1968) for assessing trend magnitude. Sometimes, if the trend analysis is conducted over different aquifers, the Sen's slope is standardized by either the maximum water level fluctuation or the interquartile range. The interest is to be able to compare trends magnitude assessed on water tables exhibiting different fluctuation ranges (<1m to >10m).

For some particular objectives, segmented trends may be used for identifying breaks in the time series and trend changes in the signal. Mann-Kendall trend test and Sen's slope are then calculated on each segment of the time series.

The main issue encountered is for attributing the detected trends to a physical phenomenon. Indeed, a common question from water stakeholder is "What is driving this trend? Can I do anything about it?" or "Is it possible to identify a trend in relation to withdrawals? Climate change?". The most used methodology to answer this question is that developed as part of the Water Framework Directive by Croiset (2018) which aims to detect significant decrease of GWL linked to withdrawals. In this report, there is a flow chart for determining whether a downward trend in GWL can be probably linked to human activities or not. Syntheses for each groundwater body are then conducted either by calculating the proportion of downward trends probably linked to withdrawals in each groundwater body, or by applying a Regional Kendall test for trend (Hirsch et al., 1982) for each groundwater body.

Another approach that we would like to investigate more in the future would be an approach based on signal processing (e.g. wavelets, empirical mode decomposition; Baulon et al., 2022a). The main asset of such approach would be to be able for disentangling the GWL signal and separate components that are linked to human activities (e.g. pumping), climate variability, and climate change. Then, trend analysis could be conducted on each component of the signal, that is the component reflecting human activities, that reflecting climate variability, and that reflecting climate change.

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Germany

Trend analysis has yet to be applied to a stand-alone task, but we have applied well-known approaches as a statistical tool on multiple projects. For instance, the statistical non-parametric test Mann-Kendall and Theil-Sen Slope are applied to assess the long-term trend of forecasted groundwater levels under climate change scenarios (Wunsch et al., 2022a). Additionally, long-term weekly averages are computed and compared to the actual observation to evaluate the current state of the groundwater level and its projections.

Regarding multi-aquifer systems treatment, we look to work mainly with shallow aquifers, identified by the filter depth; however, we are aware this is not a direct indication to say the aquifer is shallow or deep. Our main interests in applying trend analysis of groundwater heads are the potential to identify aquifers under groundwater stress and being able to relate the trend to its possible multiple drivers, whether influenced by weather/climate changes or anthropogenic factors such as over-abstraction.

Another significant point is to perform a regional clustering of piezometers (Wunsch et al., 2022b) that allows the identification of trends per hydrogeological units, jointly with an indication of the trend magnitude so adaptation measures can be proposed per area. Ideally, trend analysis assesses different time scales (ranges) together with changes in trend tendency over time. Therefore, we are interested in exploring multiple time scales from recent over-abstraction/recovery to long-term trends.

The spatial aggregation depends on data quality and availability. Overall coverage across the country covering the principal hydrogeological systems is expected when possible. However, long time series are sometimes unavailable, and trend estimation on scarce-data areas enhances the methods application.

A great benefit of the trend analysis will be to estimate groundwater depletion, in case there is one, and quantify the frequency of droughts. The estimations are essential for taking information-based solutions regarding climate adaptation.

Trend analysis approaches for groundwater heads in Europe should identify extreme events and regional groundwater patterns, which will help propose pan-European solutions and communicate with stakeholders.

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Greece

EAGME implements the underground water monitoring network (harmonised with Directive 2000/60) at national level covering the groundwater bodies of the country with 1896 monitoring stations. From 2021, 28 stations in the network are telemetric (data logging, water level and temperature). Measurements are carried out 2 to 4 times a year.

Based on the information from the stations, spatial processing is carried out per each water body and the results are evaluated annually in relation to those of past years in order to achieve the necessary picture for each system and, by extension, to apply and rationalize the management rules. For the most part, an evaluation is carried out and not a trend analysis (considering the frequency of measurements, the density of the network and the stations that, occasionally or not, are being pumped). However, in the future we can either as observers or by providing data, depending always on colleague's availability. In addition, an increase of i) density of the network and/or ii) number of measurements (every 2 or 3 months) are being evaluated. As our southern Mediterranean partners, we are looking for a method to evaluate the yearly recharge and long-term trends of our groundwater resources in relation with the fast-changing climate in our region.

Hungary

Are you currently interested in or undertaking national trend analysis of groundwater heads?

The Geological Survey in Hungary is not responsible to undertake the trend analysis of groundwater heads for WFD. This was done by the General Directorate of Water Management (GDWM) for the 185 groundwater bodies of Hungary. However, the Survey has numerous long-term groundwater level time series. These are applicable for detecting systematic changes of groundwater level and analysing trends under different hydrogeological and climate conditions.

However, we took part and were the lead institute in nationwide research to provide scientific data and analysis for the national adaptation strategy to climate change. In this research groundwater head time series were used to calibrate the regional scale numerical hydrogeological model for the different climate scenarios. (see our input to the questionnaire on machine learning subtask of WP4.1). In addition to nationwide and regional studies we are also carry-on local scale studies using our own monitoring data and data managed by the GDWM. We are very much interested in contributing to this task and developing our skills in the techniques of statistical trend analysis on different scales.

What time scale (e.g., recent over-abstraction/recovery, long-term trends) are of interest to you?

We have time series of several-decades (some cases more than 40 years) length which enables to study of over-abstractions, descending groundwater levels due to climate change or other long/short term trends of potential anthropogenic and/or natural processes.

What spatial aggregation do you use?

We are not using any spatial aggregation.

How do you treat multi-aquifer systems?

In the Pannonian Basin we can distinguishes different scale porous multi-aquifer systems depending on the resolution and aim of the project. There are monitoring sites where a group of monitoring wells with different depth operates. These wells monitor a given aquifer layer.

If you are already using trend analysis, what methods are currently in use?

We are using trend analysis for groundwater quality data with Non-parametric Mann-Kendall statistical trend test supplemented with Sen's method.

Mann-Kendall method.

Have you encountered any particular analysis-related challenges?
We had numerous challenges. Most of them related to data frequency (missing data for longer interval, changes in data frequency).

Are there additional methods you plan to use or would like to explore in the future?
We are open to any new methods.

Iceland

In Iceland the trend analysis of groundwater heads is mainly carried out by Reykjavík Energy (OR) in and around the capital area. They have a vast network of groundwater level loggers. They have not been running a standard trend analysis per se, but the groundwater levels are monitored and plotted to see if there is a trend.
ÍSOR is currently not undertaking a national trend analysis of groundwater heads. We are however interested in implementing monitoring of groundwater in relation to over-abstraction and recovery on a national scale (both short- and long-term trends). We have primarily used modular hydrologic models for analysis of groundwater heads and drawdown forecasting, almost entirely on a local scale for projects that utilize groundwater such as on-land fish farming, power-plant turbine cooling, the utilization of drinking water for local communities around Iceland etc.

Ireland

Geological Survey Ireland has recently commenced a four-year project aimed at assessing climate change impacts to groundwater. The project, being primarily carried out by a consultant, will run from 2023 to 2027 and one output of the project will be an evaluation of groundwater dynamics to detect trends and identify systems vulnerable or resilient to climate change. The goals are to:

- Develop method for the detection of groundwater extremes in current, historic, hindcasted and forecasted data. Extract and analyse groundwater droughts.
- Investigate vulnerability of groundwater systems to droughts of different temporal scales.
- Develop techniques to identify groundwater systems that are vulnerable or resilient to climate change

The project is in its early stages and the details of the methods are yet to be finalised. It is proposed to use indices to characterise and quantifying groundwater extremes, considering for example:

- The structure of groundwater observations per sites (Seasonality-magnitude; Seasonality-timing; Interannual variation; Flashiness);
- The distribution of groundwater observations per sites (Amplitude Boundness; Density; Modality); and
- The shape of groundwater observations per sites (Scale; Slope).

In addition to this project, GSI has experience of applying the Standardised Groundwater Index (SGI) to timeseries in Ireland. However, Irish groundwater timeseries seldom extend longer than 20 years and this was a limitation of the approach as it was considered that 30 years should ideally be used for standardisation purposes (as is recommended for SPI). In this context, the new 2023-2027 project will focus on developing groundwater models in order to reconstruct as many historic timeseries as possible and then convert to SGI if suitable.

Italy

ISPRA – Geological Survey of Italy is currently undertaking a national trend analysis of groundwater heads aimed to define an Indicator of Climate Change Impact on selected groundwater bodies of the Italian territory. The time scale is focussed on long-term trends. The matter of multi-aquifer systems is still not specifically and univocally faced.

We are analysing groundwater head data from selected monitoring station included within the diverse Climatic Macroregions characterizing the Italian territory. The semestral mean groundwater heads within the time series are normalized to their correspondent mean value and their variations with respect to minimum, 25th and 75th percentile values are calculated. The data related to each station are then grouped and averaged with data of other stations within the respective cited Climatic Macroregions. The trend calculations on the annual mean values are also considered according to Mann-Kendall and Sen criteria.

We think that discussion of trend analysis of groundwater heads for Europe is a big challenge. This is also due to the different meteo-climatic and hydrogeological scenarios and monitoring approach by each Member State. In any case, it is of main importance to share methodologies and start to establish common criteria on this matter.

Malta

The Energy and Water Agency is interested in undertaking trend analysis for groundwater level. Short-term analysis is of interest in the sense of determining the impacts of drought and groundwater management practices. Long-term trend analysis will also be of interest, due to the fact that we have long term data and a historical understanding of groundwater abstraction pressures.

Data is available at near-real-time scale for groundwater level and temperature, through the recently installed groundwater monitoring network. However, long-term data is also available, which in some instances, dates to as early as the beginning of the 1940s. Monitoring techniques have advanced since the 1940s, where there would have been monthly level readings, and now, where groundwater level data is taken at hourly intervals. As a result, there is the added difficulty to combine different temporal discretisation of data. Due to the natural characteristics of the two main groundwater bodies, the variations in water level is subdued since the groundwater bodies are present in the form of a floating lens on top of seawater.

EWA is interested in this exercise in order to attain a better understanding of how trend analysis is undertaken and allow the Agency to build sufficient capacity on such assessments. Collaborating with different Geo Surveys, will also enable the Agency's experts to exchange knowledge and experiences, identifying common challenges and adopting already field-tested solutions.

The Netherlands

TNO Geological Survey of the Netherlands currently provides trends for the groundwater heads in the national database of the subsurface in the groundwater head viewer (https://www.grondwatertools.nl/gwsinbeeld).

Overview

The groundwater head viewer uses predefined periods for trends of 15 years (1945-1960, 1955-1970, 1965-1980, 1975-1990, 1985-2000, 1995-2010, 2005-2010) and 25 years (1955-1980, 1975-2000, 1995-2020). The trends determined for each piezometer for each period with enough data. The trends can be viewed on map with a coloured dot indicating the trend slope for each piezometer.

Monitoring wells with significant groundwater head trends in the period 2005-2020 (from: https://www.grondwatertools.nl/gwsinbeeld).

It is possible to limit the visible piezometers the elevation of the screen or geological unit(s). Clicking on a dot in the map allows access the information of an individual piezometer. For that piezometer, the trends can be viewed for all 15- or 25-year periods in a graph and in a table. Examples for graphical representations of trends can be seen on https://www.grondwatertools.nl/gwsinbeeld.

Furthermore, an area can be selected for which a combined trend based on all selected piezometers in the area are shown.

Methods

The procedure for the trend determination is described in the online help of the Groundwater head viewer (https://www.grondwatertools.nl/gwsinbeeld). The following steps are used for each 15- and 25-year period:

1. Check whether the time interval between the first and last measurement within the period is at least 80% of the trend period. No trend is estimated if the interval is less;
2. Check whether there are more than 20 values in the trend period. Otherwise, no trend is estimated;
3. Exclude values that deviate more than 5 times the median absolute deviation from the median of the time series;
4. Resample the time series to monthly median values;
5. Resample the series to quarterly values if the previous step did not produce a series with values for at least 70% of the months. No trend is estimated if there are still more than 30% missing values;
6. Test the resampled series for seasonality and execute the applicable trend test using the pymannkendall package (Hussain and Mahmud, 2019):
   a. Use the Kruskal-Wallis test for seasonality;
   b. Determine the existence of a trend using either the seasonal Mann-Kendall test if seasonality has been detected or the regular Mann-Kendal test if no seasonality has been detected;
7. Calculate the seasonal Sen's slope or the Theil-Sen slope depending on the presence of seasonality, if a significant trend has been detected;
8. Determine the 95% confidence interval for the slope following Helsel et al. (2020), section 10.1.4, if a significant trend has been detected.

Discussion

TNO-GSN's Groundwater head viewer shows only trends for groundwater head time series. For many purposes, it is desirable to distinguish between trends due to variation of the weather (precipitation and evaporation) and due to anthropogenic influences. The time series models of the groundwater head that are also available in the Groundwater head viewer (Zaadnoordijk et al., 2019) provide information for this, but a reliable workflow is not yet available that can be automated for the viewer.

For the Dutch reporting of the quantitative status of groundwater bodies for the EU Water Framework Directive (WFD), trends in groundwater heads are assessed that are not linked to variation in precipitation and evaporation. This asks for the elimination of the variation due to precipitation and evaporation or isolation of other influences.

One approach that has been used is based on so-called structural levels of the groundwater (Leunk, 2013). A transfer-noise model of the groundwater head with precipitation and reference evaporation is created for each 6-year reporting period of the WFD. Using the models, the groundwater level corresponding to a standard amount of constant precipitation and evaporation is calculated with its uncertainty. This level is called the structural level. In principle, it contains only differences in other influences, because of using the same precipitation and evaporation for each period. The structural levels for subsequent periods are evaluated to determine whether there are declines. The applicability of this approach is limited due to the fact that 6 years often is too short to determine a reliable transfer noise model, especially in areas with slow response of the groundwater.

Another approach is to add a linear trend as explaining variable to precipitation and evaporation (Leunk, 2009). The size of the trend and its uncertainty are determined in the model calibration. This approach depends on the assumption that a linear trend mimics the anthropogenic effects well enough.

Verhagen et al. (2012) use transfer-noise models with precipitation and evaporation for the entire series as starting point. The residuals of the models are averaged over the 6 year WFD reporting periods and the differences between these averages are used to determine whether there are changes due to anthropogenic influences. Time series models for long time series are more sensitive for the generic shape of the precipitation response function – Zaadnoordijk (2022) showed that a too simple response function may lead to long term fluctuations in the residual for a groundwater system with a slow response component.

In the Netherlands, the assessment of groundwater quantity for the Water Framework directive is based on data-driven modelling of groundwater head time series (Von Asmuth, 2020). A general problem in this approach is the correlation between some anthropogenic influences and evaporation because of which the modelled precipitation response also includes (part of) the effect of e.g. groundwater abstraction for irrigation. So, the responses found in the data driven modelling ask for validation, e.g. with physics based modelling.

Needs

TNO Geological Survey of the Netherlands is working on the addition of recent data (beyond the year 2020) in the Groundwater head viewer. For the trends, this does not fit into the approach with fixed periods, so the plan is to add a trend period ending on the most recent 31st of December (which will shift each year until the end of a regular trend period is reached).

Besides this short term practical need, there is a wider need in the Netherlands for improvement of time series modelling of groundwater heads. More insight is needed in the separation of trends in groundwater heads into trends from natural and from anthropogenic influences. This is closely linked to improve the accuracy and reliability of the determination of the precipitation response and the evaporation response in transfer-noise modelling of groundwater heads.

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Poland

In Poland, groundwater trend assessment is undertaken for three tasks: for reporting under the WFD, analysis of the current hydrogeological situation in Poland and for forecasting.

The national trend analysis of groundwater heads done as part of groundwater status assessment for the WFD reporting refers to all groundwater bodies in Poland, which are multi-layered water bodies, within which water layers are grouped into 3 complexes. The first complex comprises water layers that are shallow, phreatic and in general can be in contact with surface waters and groundwater dependent terrestrial ecosystems. The 2nd complex are layers below the 1st complex, that are generally confined and not in relation to surface waters. These are usually used for water supplies. The third complex are layers that are deep and in possible contact with mineral groundwaters beneath.

Statistical analysis is done for each point separately and then a descriptive summary for each complex is formulated. The assessment is done minimum every 6 years.

Statistical analysis follows agreed rules:

- Length of data sets: min. 20 yrs
- Length of lacking data: no longer than 4 months
- Trends analysed is performed on month average data
- Level of statistical significance: 0,05
- Linear relationship models with a fit measure (R2): not less than 0.8

Due to the cyclical nature of groundwater fluctuations, we assess also the position of the current groundwater level with respect to the previous assessment and also to level zones characteristic for the multiyear period. The length of this period is minimum 10 years of observation and must include variable conditions of drought and flood.

The assessment of the current hydrogeological situation and forecasting is a systematic activity done every month or every three months, depending on the current hydrogeological status and real needs for updates. We do it for the area of the whole country and in vertical hydrogeological complexes. Length of time series has to be at least 20 year and trends are analysed using rectilinear curve. For seasonal forecasts, we have developed a model based on the rate of descent and fall of the water table in different months/seasons. Forecasts are developed for two extreme scenarios.

In addition, we have recently built a model based on MODTW - based on the article Influence of low-frequency variability on groundwater level trends (Baulon et al., 2022) and others, on which the above-mentioned work is based. We are in the process of testing it for various hydrogeological conditions. When building a model based on MODTW, we had a problem with determining the periodicity of the fluctuation component in a systematic way to make a prediction, but in the end we found a fit that we think works well – we need to test it on more points now.

For the trend analysis of groundwater heads for Europe we think that we should first set the goals for forecasting and clearly define water levels we want to analyse, for example, to specify the maximum depth of the top of the groundwater levels we want to include in analysis.

Romania

Geological Institute of Romania (IGR) is currently interested in national trend analysis of groundwater heads. At the same time, we can mention that IGR has signed a cooperation protocol with the National Institute of Hydrology and Water Management (INHGA), which collects data and administrates the underground aquifer databases. The protocol foresees that, in exchange for the data that INHGA provides to IGR, this institute will benefit from the results of the GSEU project - WP4. As a consequence, they will be able to implement at national level the forecasting methodologies developed in the GSEU project.

Regarding the time scale, IGR is interested in long-term trends.

Regarding the spatial aggregation, in Romania, for an aquifer, daily measurements in two or more boreholes are used.

Concerning multi-aquifer systems, in general, distinct boreholes are used to study each intercepted aquifer. This rule is applied in the case of observation drill holes (which, in particular, provide the data for trend analysis of groundwater heads) but it is also a rule for extraction, as well, so that any contamination between aquifers be avoided.

For trend analysis, we compare the current registered monthly values with multiannual monthly values. So far, we cannot say we have encountered any particular analysis-related challenges, but we do not exclude such challenges while extending our collaboration with INHGA.

For the time being, we do not plan to use additional methods for trend analysis of groundwater heads.

Regarding the trend analysis of groundwater heads for Europe, we consider this type of analysis should be used to all phreatic aquifers in Europe, using similar methods. A unique reporting template needs to be established, as well.

Serbia

Geological Survey of Serbia did the time series analysis for the purposes of the GeoERA TACTIC Project. Nowadays there's a new National Project in Geological Survey of Serbia Impact of climate factors and surface waters on groundwater quantity and quality in Vojvodina which will be in progress from 2023 to 2027. The aim of this project is, also, to use the data and the results for participation in WP4 GSEU Project. The data collected will be used for machine learning models and for time series analysis.

Geological Survey of Serbia is not the owner of the Monitoring data and network of groundwater on a National level. Nevertheless, we have obtained the data from other Governmental Organization who is the owner (Republic Hydrometeorological Service of Serbia). GZS is now in the possession of the monitoring period from 1990 to 2022 (daily and monthly average data) and plans to use it for the trend analysis as proposed in GSEU.

The groundwater monitoring is carried out in observation wells (piezometers) in shallow aquifers (intergranular porosity) in the Northern part of Serbia. The idea is to develop a method for the groundwater extremes (flood and drought).

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Slovakia

Are you currently interested in or undertaking national trend analysis of groundwater heads? What time scale (e.g., recent over-abstraction/recovery, long-term trends) are of interest to you? What spatial aggregation do you use? How do you treat multi-aquifer systems?

In Slovakia, SHMI – Slovak Hydrometeorological Institute is the governmental organization in charge of groundwater levels monitoring at least since 1940s. Štátny geologický ústav Dionýza Štúra – Geological Survey of Slovak Republic (SGUDS) – is in charge of construction of hydrogeological maps, estimation of groundwater resources and monitoring of groundwater quality around contaminated sites (if only activities close to groundwater are selected). SGUDS is still allowed to use the SHMI data on groundwater levels monitoring, when dealing with particular projects and programs (supported by the Ministry of Environment), but is not allowed to share these with the third party

It follows from the above that SHMI – Slovak Hydrometeorological Institute is undertaking national trend analysis of groundwater heads, and SGUDS – Geological Survey of Slovak Republic is in some cases involved in recent over-abstraction/recovery problems as the data have to be purchased from SHMI. SGUDS interest in participating in the project is therefore more methodological (to learn from the GSEU colleagues) than data handling and processing

In these days, SHMI monitoring network of groundwater levels counts 1147 wells, mostly in shallow Quaternary aquifers of river alluvia, not deeper than 10 m, but 80 wells are deeper, designed for pre-Quaternary aquifers (this is how treat multi-aquifer systems are treated). From these 1147 wells, in 971 groundwater levels and water temperatures are monitored in hourly intervals. These automated stations were set into usage since 2000 – 2005, before this, weekly observation intervals were performed mostly for five three to four decades what is still performed at 176 wells.

If you are already using trend analysis, what methods are currently in use? Have you encountered any particular analysis-related challenges? Are there additional methods you plan to use or would like to explore in the future?
SGUDS expects to learn from colleagues with better access to data

Can you highlight any additional information such as publications, reports, or web links related to the methods you are currently employing or wish to use in the future?
the same as above

What are your ideas about trend analysis of groundwater heads for Europe?
the same as above

Slovenia
Geological survey of Slovenia conducts trend analyses in various studies, mainly at the local scale. We are interested in short- and long-term groundwater level trends. How to define trend analysis in the multi-aquifer systems is not specified.

For our only official geothermal aquifer, we calculate groundwater level trends based on the method used by the Slovenian Environmental Agency (Andjelov et al., 2006), using groundwater level data from year 2009 on. This method is originally intended for the assessment of quantitative status in shallow aquifers with predominant intergranular porosity, to determine the assessment of the status of 21 groundwater bodies in Slovenia, but we believe that the method can also be used to assess the groundwater trend line in deep geothermal aquifer. We are checking the reliability of the trend line by Spearman's rank correlation coefficient and Student's statistical test based on 95%.

For individual locations, we have also carried out statistical analyses of groundwater level diagrams of individual groundwater stations, which can be used to determine periods of groundwater drought (Adrinek & Brenčič, 2019). We use the method based on ranking statistics defined by lower percentiles, which indicate low groundwater levels. Another method we have also used in the past is based on the univariant Standardized Groundwater Index – SGI. One of the challenges in our analysis was the lack of longer groundwater level time series and spurious spatial distribution of stations in the past. Another important challenge is the improvement of the aquifers boundary conditions, which have changed several times during the whole monitoring period due to anthropogenic influences (we have some data from 1960 onwards).

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Spain (IGME)
Overview

Since 2002, the Environment Ministry has tasked river basin authorities with managing piezometric levels. For the time being, there are approximately 2,500 monitoring stations. Many of them come from the IGME network, others come from autonomous community administrations and others are newly built. The autonomous communities of Andalusia, the Balearic Islands, the Canary Islands, Catalonia, Galicia and the Basque Country are responsible for the management of groundwater in the intra-Community basins, which are entirely within their territory. Sampling frequency is monthly at many of the monitoring network stations, but there are also sampling points with bi-monthly or bi-annual frequencies. A small number of piezometers have been equipped with automated measurements, with a daily frequency.
Trend analysis is carried out for the whole series at individual monitoring stations, although when the behaviour of several piezometers in a Groundwater Body or a larger area is to be analysed, the same time period is used to make comparisons.

Methods
In large, the most commonly used method are the Mann Kendall trend test (Grima et al., 2023) and Sen's slope. Although annual averages have sometimes been used for comparison (Mejías and del Pozo, 2020), they are not as widespread as the aforementioned methods.

The modified Mann Kendall test, to take into account autocorrelation, has not been commonly used. In specific studies, the Regional Kendall test of trend significance has been used for spatial aggregation. On the other hand, multi-layer aquifers have not been generally considered in network design.

Discussion
The common goal and yet the biggest challenge when analysing trends is to separate the influence due to different causes, such as climatic variability and anthropic factors, mainly due to water extractions. Among the research interests of IGME are the analysis of the influence of climatic factors, basically precipitation and temperature and spectral analysis, in order to relate the fluctuations of the piezometric level with climate change.

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Spain, Catalonia (ICGC)
In Catalonia trend analysis of groundwater heads are done by the Catalan Water Agency (ACA) for the internal basins and by the Ebro Hydrographic Confederation (CHEBRO) in the Ebro River basin. They are made for the WFD groundwater bodies considering monthly measurements and a temporal length of minimum 10 years. The Mann-Kendall test (Mann, 1945; Kendall, 1975) is applied to estimate the trend and its degree of significance, together with the slope of the trend Sen estimation (Sen, 1968). The obtained results are used to design the River Basin Management Plans.

Any improvement in the trend analysis estimation method will be of high interest to reveal patterns of change in aquifers recharge and discharge. This information in Catalonia is essential for assessing the sustainability of groundwater use and anticipating potential issues such as overexploitation or saline intrusion. Furthermore, monitoring the trend of piezometric levels facilitates the identification of areas at risk of water depletion, enabling the implementation of preventive and corrective measures to ensure the continuous availability of groundwater.

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Sweden

We have not published any data or report regarding trend analysis of groundwater heads, but we have carried out some analysis of time series of groundwater levels for internal use. So far, the objective has been to characterize the properties of individual monitoring stations. The methods are:

- Trend analysis to evaluate temporal changes in site properties.
- Fourier analysis to quantify period lengths.
- Temporal autocorrelation.
- ANOVA to estimate the within-year-variation in relation to the between-year-variation.

Issues that we have discussed have for the most part concerned reasons for observed trends. An observed trend could be interesting in itself, but I think that the value of the observation is much greater if the reason for the trend is clarified. For example, if an observed trend is due to local human impact (e.g. pumping) or climate change. However, it could be difficult to determine.

We are using non-parametric methods to deal with data from monitoring of groundwater chemistry and we have thought of using it also for groundwater levels as well. However, we have not had the resources yet to realize it. We are using Mann-Kendall to estimate the significance levels and Theil-Sen to quantify the trend.

United Kingdom

We've answered the survey questions in a summary manner before giving some more detailed context as additional information below.

- Are you currently interested in or undertaking national trend analysis of groundwater heads?
- What time scale (e.g., recent over-abstraction/recovery, long-term trends) are of interest to you?

Yes, currently interested in or undertaking national trend analysis of groundwater heads. We are primarily interested in understanding the long-term, muti-decadal, trends in groundwater heads as a function of changes in driving climatology (climate change) and associated catchment characteristics particularly as they effect groundwater droughts. We have secondary interests in trends in groundwater heads at the decadal time scale as a function of decadal scale teleconnections, e.g. changes in groundwater as a potential function of El Nino / La Nina and NAO (Rust et al, 2022). We don't have any strong interest in exploring trends in groundwater heads related to over abstraction or groundwater rebound as these are not major issue in the UK and are where they do occur are treated as regional or local management issues.

What spatial aggregation do you use?
We don't use a particular spatial aggregation for any of our analyses. Typically, we will characterise groundwater hydrographs at an individual site level and then if we are using cluster analysis to search for similar responses to changing climate or other factors this will cover the entire study area which may be a region, an aquifer (such as the Chalk), or will be at the national scale. There is one exception to this in that when estimating the UN Sustainable Development Goal 6.6.1: groundwater sub-indicator 5 for the UK the methodology required that observations were aggregated over HydroBASINS, typically of the order of 100 to 200 km^2.

How do you treat multi-aquifer systems?
There are relatively few muti-aquifer systems in the UK compared with the rest of Europe. The two main aquifers in the UK are the Cretaceous Chalk and the Permo-Triassic sandstones and both are primarily exploited across their unconfined extent. Consequently, where assessments are made of trends in groundwater heads data from unconfined and confined aquifers is typically treated in the same manner. However, in most cases data from confined observation boreholes (OBHs) may be screened out prior to analysis and even if it isn't the analyses will consist of primarily or entirely data on unconfined heads since this constitutes most of the observations in the UK.

If you are already using trend analysis, what methods are currently in use?
We have used a range of approaches to characterise changes or trends in groundwater heads. Thes include:

- Visual inspection of groundwater head hydrographs
- Description of the changing rank of groundwater heads at a given site over time
- Fitting simple linear regression models to groundwater heads
- Formal Mann-Kendal and associated Sen slope tests of groundwater head hydrographs
- Clustering of multiple standardized groundwater level (SGI) hydrographs and identification of clusters with trends

Have you encountered any particular analysis-related challenges?
Length and quality of observational records and consistency of these between sites are typically the main issues. When coming to analyse and interpret the results of any trend analysis the main issues in the UK are the typically limited borehole metadata and information regarding aquifer properties in the immediate vicinity of the observation borehole.

Are there additional methods you plan to use or would like to explore in the future?
We would be interested in combining historic observational data with reconstructed groundwater level data and modelled future groundwater levels at selected well-constrained / well-understood sites across the UK to investigate changes in groundwater heads over the centennial scale from ~1900 to ~2100 and relate this to changing climate, catchment characteristics and long-term changes in the management of water resources in the UK. Clearly, one of the main challenges of such work would be to understand the uncertainties associated with the reconstructed and modelled future heads.

Can you highlight any additional information such as publications, reports, or web links related to the methods you are currently employing or wish to use in the future?
These are listed at the end of the Additional information section below.

What are your ideas about trend analysis of groundwater heads for Europe?
Almost all the observational records of groundwater heads across Europe will be too short to investigate and quantify the effects of climate change and associated long-term, multi-decadal change in catchment characteristics. Conversely, patterns of annual to sub-annual trends in groundwater heads across Europe can be expected to be highly variable, contingent of aquifer types, catchment setting, and local water resource management practices. However, it would be useful to identify regions or areas across Europe where there have been decadal-scale changes in groundwater heads.

In natural systems, these should be associated with decadal scale variations in driving climatology (that may or may not include a component of longer-term anthropogenic climate change). Clearly, the response of the aquifer to the driving climatology will be a function of the aquifer characteristics but if groundwater head trends and trends in the driving climatology are correlated then it can be inferred that the heads represent systems relatively unimpacted by anthropogenic activities. Where there is a deviation between the decadal-scale trend in groundwater heads and the decadal scale variation in driving climatology then it could be inferred that declining trends in heads may be due to over abstraction or that rising heads could be due to a reduction or cessation in groundwater abstraction over the corresponding period.

Mapping sites, areas or regions that show either relatively natural trends in groundwater heads (driven by trends in climatology) and sites, areas and regions that show trends in groundwater heads that are inferred to be impacted by groundwater over abstraction or groundwater rebound would be helpful in an assessment of the spatial variability in vulnerability of groundwater systems to drought.

Additional information
The British Geological Survey (BGS) reports on the status of groundwater levels in the UK on a monthly basis through as part of the Monthly Hydrological Summary available at https://nrfa.ceh.ac.uk/monthly-hydrological-summary-uk, and on near real-time data through their website at https://www2.bgs.ac.uk/groundwater/datainfo/levels/home.html through the UK Water Resources Portal at https://nrfa.ceh.ac.uk/content/uk-water-resources-portal. The Monthly Summaries of groundwater levels map groundwater status at about 35 observation boreholes as one of seven categories ranging from ‘exceptionally low’ to ‘exceptionally high’ and include a note of the rank of that month’s observation in the context of the whole observation record. Additional text summarises the month-on-month change in status of groundwater. So, although this is not a formal trend analysis it does indicate monthly change. However, there is no formal national-scale real-time trend analysis currently undertaken for groundwater level time series from the UK. This reflects the observation that in the UK at the national scale over-abstraction, and recovery from over-abstraction, are not significant issues and so there is no strong driver to monitor shorter-term trends in groundwater level (i.e. seasons to a few years). Historically, where there has been the possibility of local over abstraction and of groundwater level rebound (for example following the cessation of groundwater abstraction following closure on mines or de-industrialisation of UK urban centres). This has been investigated by the environmental regulators and abstractors / industry on a case-by-case basis and BGS has not typically been involved.

Bloomfield et al. (2003) used simple multiple linear regression of groundwater level data from three observations boreholes from the UK to investigate trends in the levels and the co-correlation with related rainfall records to investigate the potential impacts of climate change on annual minimum levels.

As part of the UKs commitment to publish progress against the UN's Sustainable Development Goals, BGS published data regarding the Sustainable Development Goal 6.6.1: groundwater sub-indicator 5 – quantity of groundwater within aquifers for the period 1990 to 2019 (Bloomfield et al, 2021a). This used the UN-approved method to estimate changes in decadal scale groundwater levels to investigate and characterise over abstraction and recovery from over abstraction at a regional level in the UK (UNEP, 2021). Note the detailed methodology used in the UK is available in the Supplementary Information to Bloomfield et al (2021b). Assessments were carried out by aggregating observations over HydroBASINS (HydroBASINS, 2024) (typically of the order of 100 to 200 km2) and ignored the effects of layered aquifers by combining trends seen in surface and confined aquifers where they occur in the same HydroBASIN. Application of the method indicated no regionally significant changes in groundwater levels in the UK over the period 1990 to 2019, with the exception of the HydroBASIN representing the Mersey region of NW England where groundwater rebound in unconfined and confined aquifers of the Cheshire Basin was noted.

BGS is interested in longer-term changes in groundwater resources and how these may change under climate and other long-term environmental changes. As part of a review of evidence for changes in historic and future groundwater levels in the UK, Jackson et al (2015) described the results of a trend analysis applied to seven long groundwater level records covering the period 1900 to 2006 with a minimum length of 40 years. All sites were in the same unconfined aquifer (the Chalk, a Cretaceous fractured, dual-porosity carbonate sub-karstic limestone) although widely spatially distributed within the UK. They used the Mann-Kendall test as implemented in R package 'Kendall' (Hipel and McLeod, 1994), Kendall's tau and its significance level were estimated for each of the sites to test for the presence of significant trends. The trend test was applied to the normalized SGI data so that seasonality in the groundwater level data was removed prior to testing for trend. It was found that at all but one of the sites showed a decline in groundwater levels over the respective observation periods and that this decline is significant at the p=0.05 level for four of the sites which importantly included the two longest records. The authors noted that it is difficult to unambiguously identify trends in hydrological time-series and ascribe them to climate change (Wilby,2006), and that the results of the Mann Kendall tests do not in themselves provide direct evidence for the impact of climate change on groundwater levels. However, in a subsequent study of changes in drought occurrence over time at two of the sites, Bloomfield et al (2019) did attribute increases in drought frequency and magnitude to long-term warming associated with climate change.

Although not specifically designed to identify and quantify trends in groundwater level data, as part of a series of investigations of groundwater drought histories in the UK, Bloomfield a co-workers have shown that cluster analysis of Standardised Groundwater level Index (SGI) time series often results in one or two clusters exhibiting increasing and / or decreasing groundwater levels trends (Bloomfield and Marchant, 2013; Bloomfield et al., 2015; Marchant and Bloomfield, 2018) and where membership of these clusters has been inferred to indicate the effects of anthropogenic activities, i.e. clusters with declining groundwater levels are typically associated with local over abstraction and clusters with rising levels associated with groundwater level rebound. In each of these studies standardisation of levels was undertaken on a borehole-by-borehole basis but the clustering was undertaken across the whole study area, approximately in the range 5,000 to 50,000 km2. The period of analysis was typically 30 years or more to enable SGI to be estimated. Groundwater level time series from unconfined were the primary targets of the analysis and constituted most of the observations although no account of the degree or nature of confinement was taken into account during clustering.

MacAllister et al (2022) developed methods to look at anthropogenic influences on groundwater level trends at the centennial scale 1900 to 2010 across Pakistan and NW India. Using only post monsoonal data, mean groundwater levels in OBHs were estimated on a decadal basis with a minimum of six data points in each decade. A bootstrapped version of the non-parametric Mann-Kendal trend test was then used to quantify trends and estimate slopes.

Marchant et al (2022) have shown how mixed models can be used to temporally interpolate groundwater level hydrographs for regional drought analysis, including for hydrographs that show both increasing and decreasing trends in levels. This approach was applied to data from five OBHs across the UK over a period of 35 years between 1980 and 2015.

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Ukraine (UAG)

Groundwater head trend analysis is a powerful tool that can be used to address specific needs at the national-scale level primarily for water management. Its potential benefits to the specific needs are the following (just a few of the main ones are mentioned here):

- Forecasting and preventing catastrophic processes triggered by the rise of groundwater levels (flooding, submersion of territories);
- Decision-making on the optimal operation mode of water intake to prevent depletion of groundwater;
- Developing measures to prevent hazardous phenomena related to the development of salt karst during technogenic interventions in the formations of rock and potash salts;
- Maintaining sustainable quality of exploited groundwater by identifying trends affecting qualitative indicators at early stages;
- Improving the efficiency of groundwater use and reducing expenditures;
- Planning the structure of water supply and irrigation systems, etc.
- It should be noted that full trend analysis involves identifying and accounting for factors influencing changes in groundwater pressure, such as climate change, anthropogenic activities, and geological processes.

Currently, Ukraine is keenly interested in the national trend analysis of groundwater heads, more so than any other country. This is due to a hydrogeological (water) catastrophe in the central part of Ukraine, resulting from the dam explosion at the Kakhovka Reservoir by the Russian aggressor. This incident led to a regional decline in groundwater levels and the disappearance of water in certain water abstraction areas. The primary solution to address this issue involves conducting hydrogeological studies, including monitoring, which entails drilling new wells. Currently, this is a challenging task due to ongoing shelling in the affected area. For a comprehensive assessment of the situation, monitoring data from at least the past 10 – 15 years must also be included in the trend analysis.

The Ukrainian Transcarpathian region presents another challenging area due to regular floods and inundations. For this region, groundwater head trend analysis is critically needed to forecast large-scale floods.

A key aspect of transitioning to sustainable water management is organizing regional groundwater monitoring, covering all designated groundwater reservoirs. Recently (pre-war), monitoring was conducted within specific local regions for particular consumer purposes, within the hydrogeological unit of a single water intake. However, during wartime, monitoring is absent in a significant portion of Ukraine. Therefore, the analysis is possible only for individual local hydrogeological units.

Regarding trend analysis methods, Ukraine has established a methodological foundation. Successful analysis requires a comprehensive database created from the results of long-term regional monitoring of the hydrodynamic component. However, as of today, the database is relatively scarce due to the aforementioned reasons.

Methods used for trend analysis typically involve mathematical-statistical analysis (using time series) and modeling hydrodynamic processes of various levels, including the construction of analog, digital static, and dynamic models.

1) Analog modeling is employed to address specific tasks for a local area. Analog models are often manually constructed using programs like Excel and graphic editing software such as CorelDRAW.
2) Digital modeling integrates the existing database and task requirements into a unified information and analytical system (GIS). Oracle Database is commonly used for data collection, processing, and storage. However, a significant portion of the data has a disunited character and does not enter this system.
3) Mathematical modeling enables the creation of predictive geofiltration mathematical models with spatial analysis in GIS. It involves mathematical-cartographic modeling of hydrodynamic head fields and mathematical-statistical methods for analyzing and assessing the distribution of hydrodynamic heads of groundwater.

In the case of significant monitoring data deficiency, a method of remote sensing of groundwater head, combined with geobotanical descriptions, is also employed. This method is applied exclusively for thick, laterally continuous groundwater horizons.

When studying a system with multiple aquifers, a selectively analytical method is used to specify the task. In cases where a hydraulic connection between aquifers is established and proven, specific tasks can consider them as a unified aquifer complex within a basin (sub-basin). For instance, this approach classifies the aquifer complex of suprasalt stratum covering the Artemivsk rock salt deposit (Dnieper-Donetsk Depression, eastern Ukraine).

To obtain more accurate trend analysis results, various methods and their combination are used. The best results are achieved through a systematic approach.

The main problem in Ukraine is the imperfect system of groundwater monitoring and an imperfect database due to the residual principle of financing these works. This is in contrast to the current system of monitoring water resources in Europe, where multi-level monitoring principles are applied in accordance with the Water Framework Directive.
In the future, I would also like to use more advanced hydrodynamic modeling using the latest software systems and artificial intelligence.

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http://www.geol.univ.kiev.ua/lib/MHGR-2015.pdf

IGS is not currently employing trend analysis of groundwater heads on a routine basis.

However, IGS is interested in exploring and acquiring experience in relevant methods of trend analysis, and applying it to existing data sets, as well as for groundwater level forecasting at specific sites. In particular, IGS is involved in groundwater analyses at several historic heritage sites such as Kievo-Pecherskaya Lavra Monasteryand St. Sophie Cathedral in Kyiv. Here, an increase of groundwater levels can cause geotechnical stability problems, because the unsaturated soil zone is composed of loess deposits, which can loss structural integrity at high water content, and are subject to subsidence. Very often, dangerous increases of groundwater levels are caused by leakage from subsurface pipes for water supply, heating or for storm runoff collection. In such a situation trend analysis can assist with an early detection of a problem, so that measures to address the problem could be taken. In the discussed case trend analysis can be employed at a scale of “weeks– months” (e.g., dictated by frequency of observations).

Groundwater heads trend analysis is also of interest in connection with assessing impacts of human activities in urbanized environments (e.g., losses/leakages from subsurface water supply/heating/sewage networks in large cities), depletion of water resources due to pumping, and effects of global climate changes on groundwater resources. Here trend analyses can be carried out at the scale of “years – decades”. All these applications are of potential interest to Ukrainian scientists and engineers.