Journal of Hydrology 669 (2026) 135027

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Integrated multi-scale ecohydrogeological monitoring of spatio-temporal dynamics in karst critical zones

Nataša Ravbar[a,b,*], Metka Petrič[a,b], Mitja Ferlan[c,d], Uroš Novak[a,b], Janez Kermavnar[c], Lado Kutnar[c], Aleksander Marinšek[c], Daniel Žlindra[c], Blaž Kogovšek[a,b], Erika Kozamernik[c], Cyril Mayaud[a,b], David Štefanič[c], Sara Skok[a,b], Janez Mulec[a,b], Stanka Šebela[a,b], Urša Vilhar[c]

[a] Karst Research Institute ZRC SAZU, Titov trg 2, SI-6230 Postojna, Slovenia
[b] UNESCO Chair on Karst Education, University of Nova Gorica, Glavni trg 8, 5271 Vipava, Slovenia
[c] Slovenian Forestry Institute, Večna pot 2, SI – 1000 Ljubljana, Slovenia
[d] Slovenian Environment Agency, Vojkova cesta 1b, SI – 1000 Ljubljana, Slovenia

ARTICLE INFO

This manuscript was handled by Amilcare Porporato, Editor-in-Chief

Keywords:
Karst
Integrated monitoring
Interdisciplinary strategy
Hydrological processes
Environmental management
Ecohydrology

ABSTRACT

Contemporary environmental concerns highlight the vulnerability of karst environments to changing hydrometeorological patterns and vegetation disturbance, necessitating a unified, interdisciplinary strategy for comprehensive understanding. This paper critically examines the current state of research. To overcome the identified gaps, it presents an integrated multi-scale ecohydrogeological monitoring approach tailored to karst critical zones (KCZ) and its spatio-temporal variability. Forested karst aquifer in Slovenia is used as a case study to demonstrate and assess the strengths and limitations of the proposed monitoring framework. To decipher flow dynamics and propose customized data collection strategies the approach combines surface and underground sites and employs advanced methods adapted to the challenges of karst environments. The results highlight the benefits and advancements of monitoring and sampling approaches to ensure representativeness in heterogeneous environments. The focus is on the use of enhanced precipitation monitoring systems to expand sampling areas nearly fivefold and improve precipitation and throughfall measurements. Additionally, customized lysimeter techniques for karst soils and microscale adaptations for cave exploration have been developed, addressing the challenges of instrument placement in environments with significant variability. Further opportunities lie in improving instrument protection, integrating sensor networks, combining remote sensing and scaling from plot to aquifer level. However, challenges remain in achieving spatio-temporal representativeness and ensuring the operational reliability of snow monitoring, soil solution sampling and drip flow measurements. Threats include environmental pressures and hydrometeorological conditions, equipment tampering and funding stability. Nevertheless, this comprehensive approach improves monitoring of ecohydrogeological processes in the KCZ, promotes interdisciplinary collaboration and environmental resource management.

1. Introduction

Contemporary society faces escalating concerns over the impact of changing hydrometeorological patterns, extreme weather events and natural disasters, as they can affect vegetation cover, water cycle and other ecohydrogeological processes (Condon et al. 2021, Pörtner et al. 2022). Among the vulnerable environments, aquifers with karst porosity stand out due to their highly dynamic hydrological processes, making them extremely susceptible to the effects of diverse environmental disturbances (Ford & Williams 2007).

Karst aquifers, covering around 15 % of the global land surface and up to a fifth in Europe, are crucial water resources, supplying a significant portion of the world's drinking water needs (Hartmann et al. 2014; Stevanović 2019; Goldscheider et al. 2020). At the same time, karst areas offer priceless ecosystem services that include unique, groundwater-dependent habitats with high biodiversity and thus genetic material (Siegel et al. 2023). As the demand for karst water increases, it is essential to understand and monitor the potential impacts of changing

* Corresponding author.
E-mail address: natasa.ravbar@zrc-sazu.si (N. Ravbar).

https://doi.org/10.1016/j.jhydrol.2026.135027
Received 13 May 2025; Received in revised form 23 January 2026; Accepted 24 January 2026
Available online 30 January 2026

environmental conditions on karst hydrology and ecology. Neglecting these changes could lead to long-term consequences such as water scarcity or floods, poor water quality, habitat degradation, and other adverse effects on karst hydrology (Long et al. 2018; Kovačič et al. 2020; Klaas et al. 2020; Morrissey et al. 2021). On the other hand, the integration of data on a regional and global scale and the simplified assessment of a large amount of quality data greatly contributes to advancing the field of karst hydrology (e.g. Goldscheider et al. 2020; Olarinoye et al. 2020).

Recent studies suggest that the effects of changes in vegetation cover have important implications for hydrological processes, but these are poorly understood. The existing studies mainly focus on non-karst environments and are limited to the plot level (Carrière et al. 2020; Tramblay et al. 2020; Vilhar et al. 2022). In studies conducted in karst areas, there is a notable gap in comprehensive research, particularly regarding the processes of infiltration, recharge and groundwater flow through the aquifer. Issues related to the quality and quantity of water resources are also poorly researched, and there is a significant lack of holistic regional studies that assess the broader impacts on karst hydrology (Vilhar et al. 2022). Such studies require monitoring to ensure the collection of consistent and reliable data throughout the research process.

Current monitoring sites worldwide, established for various research purposes related to karst ecohydrology, lack a coherent approach that addresses the complex nature of karst areas, which encompasses multiple environmental domains. These sites also suffer from interdisciplinary gaps with poor involvement of experts from different disciplines (Cantonati et al. 2020). Technical challenges such as difficult access, inadequate sampling equipment and the complexity of direct hydrological measurements in the soil and underground further hinder the assessment and quantification of groundwater recharge in karst areas at a regional or catchment scale. The diverse topography in a small area, characterized by impassable areas of dolines and karrenfield, adds to the complexity (Breg Valjavec et al. 2022).

The heterogeneity of the karst relief further determines extremely high variability of soil conditions and diverse forest development stages, which makes the identification of representative monitoring sites a challenge (Kobal et al. 2015). Although underground speleological research provides *in situ* studies and some insights into underground structure and water flow (Heimel & Tobin 2022), most water caves are rarely accessible. Furthermore, there are few study sites with a large number of boreholes that would allow representative interpolation of hydrogeological information on a larger scale. Although conventional methods such as pumping tests provide valuable data, they only reflect the conditions surrounding a well and generally do not characterise the aquifer as a whole (Stevanović et al. 2024). Sampling from the soil or from underground watercourses is also problematic as samples can be difficult to collect and quite turbid requiring additional laboratory handling.

In recent years, promising non-invasive field methods, including remote sensing, computer and artificial intelligence techniques such as numerical modelling and machine learning, have shown the potential to provide new insights into recharge and flow processes in karst (Watlet et al. 2018; Wunsch et al. 2022; Cinkus et al. 2022). However, the lack of reliable field data and the considerable surface and underground heterogeneity of the aquifer restricts the application of advanced research methods (Sarrazin et al. 2018). In addition, existing hydrological models tend to overgeneralize the groundwater flow system, as they are often highly simplified and not always sufficiently calibrated to field measurements. Furthermore, there is a lack of cooperation among different disciplines to integrate hydrological and biological processes over varied spatial and temporal scales in karst aquifers, although strong and direct interaction exists between the circulation and storage of groundwater, surface water and the spatial distribution of organisms in karst habitats (Bonacci et al. 2009; Vilhar et al. 2022).

In response to these challenges, this study advances the monitoring of complex ecohydrological processes in karst critical zones by addressing key research gaps through an innovative, multidisciplinary approach (Moore et al. 2015; Seidl et al. 2017; Mollenhauer et al. 2018). Specifically, it aims to strengthen the foundation for further research by i.) critically reviewing the state of the field and identifying key research gaps, ii.) proposing a unified monitoring strategy that integrates the various factors influencing karst ecohydrology and focuses on spatial and temporal variability, and iii.) assessing the strengths and limitations of an established monitoring network in a forested karst aquifer.

By integrating these objectives, this study presents a multi-scale approach to elucidate flow and transport mechanisms and optimize data collection throughout karst critical zones. It provides new insights into karst ecohydrogeology at the intersection of atmosphere – geosphere – hydrosphere – biosphere and offers a globally unique perspective on this highly relevant topic. Such an integrated framework is essential for the development of effective management strategies, as karst systems are highly sensitive to surface activities that affect water resources, biodiversity and soil stability.

2. Karst critical zone

This section first defines the concept of the Karst Critical Zone (KCZ), followed by a critical review of the current state of ecohydrological monitoring in karst environments, highlighting key research gaps. Building on these findings, we propose a unified monitoring strategy that integrates various factors influencing karst ecohydrology, with a focus on spatial and temporal variability. This framework is designed to guide the development of more effective, integrative monitoring efforts across karst systems.

2.1. Definition and Conceptualization

Critical Zone (CZ) research, which investigates the controlling factors and comprehensive mechanisms regulating natural processes and resource availability in the Earth's near-surface system, has become a central focus of environmental science in recent decades (Ashley 2001; Lee et al. 2023). The CZ is defined as the land surface and its vegetation, overlying the soil, unsaturated zone, and saturated groundwater zone. It encompasses the intersection of the atmosphere, geosphere including lithosphere and pedosphere, hydrosphere, and biosphere (Chorover et al. 2007; White et al. 2015), although the physical boundaries remain controversial among scientists. In addition, research in these areas contributes to progress in the socio-economosphere (Mollenhauer et al. 2018). Carbonate terrains are integral to the CZ hereafter referred to as the karst critical zone (KCZ; Fig. 1).

2.2. Review of current monitoring practices and research gaps

A comprehensive review of the state of knowledge on carbonate critical zones by Covington et al. (2023) highlights the research gaps and emphasises the need for integrative studies across the entire spectrum of carbonate and silicate landscapes for a holistic understanding of the Earth's critical zone.

Similarly, Vilhar et al. (2022), who conducted a comprehensive review of nearly 50 studies in karst areas, highlighted the scientific importance of ecohydrological research in these environments. However, they emphasized that most existing studies are limited to the plot scale and primarily focus on forest management and land-use change. While the effects of forest management on evapotranspiration and recharge dynamics are well studied, fewer studies address soil processes or groundwater recharge and flow at depth. Large-scale disturbances affecting evapotranspiration, for example, are better studied than infiltration and recharge in karst systems, because the main hydrological processes are still poorly understood.

Among the studies compiled by Vilhar et al. (2022), this review focuses on those based on comprehensive field measurements and

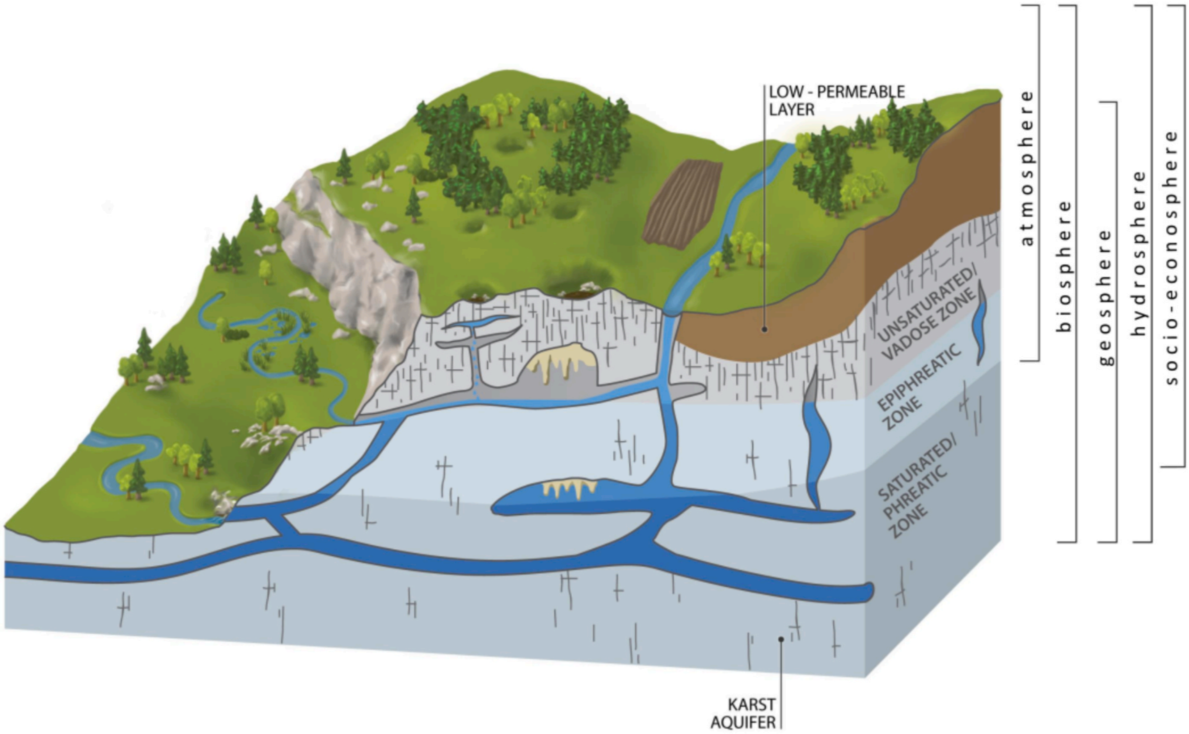

Fig. 1. Schematic representation of the karst critical zone (KCZ), linking atmospheric inputs (precipitation), biosphere and soil processes, epikarst (upper part of the vadose zone) and vadose-zone flow, and the saturated aquifer. The sketch serves as a conceptual basis for integrating monitoring data across spheres (modified after Ravbar & Šebela 2015).

specifically aimed at investigating recharge processes. In most of them, the monitoring network included measurements of precipitation and meteorological parameters as well as soil water content; the influence of different vegetation properties was only tested by setting up the monitoring network in different vegetation types (Cantón et al. 2010; Heilman et al. 2012; Ferlan et al. 2016; Li et al. 2023). More detailed studies on the influence of vegetation and the processes of interception and evapotranspiration additionally included measurements of throughfall (Katzensteiner 2003; Vilhar & Simončič 2012) and sap flow (Ungar et al. 2013). However, the subsurface flow was not observed. There are also many hydrological studies using long-term hydrological and meteorological data to calculate water balance components, including evapotranspiration, runoff, and changes in water storage, to analyze temporal and spatial variations in the main water cycle fluxes or to investigate the relationship between meteorological conditions and karst spring discharge dynamics, but not taking into account hydrological cycle within vegetation and soil layers (Mahler et al. 2021; Hartmann et al. 2014). In this respect the study of Mueller et al. (2013) stands out, who investigated precipitation and stream base flow to characterize subsurface flow paths and storage dynamics in four catchments with varying vegetation cover to assess how topography and land cover influence base flow generation and water flow regulation. Similarly, Cao et al. (2025) investigate the effects of agricultural land use on hydrological and geochemical processes in a subtropical karst basin in southwest China. The study is based on high-frequency hydrological monitoring and hydrochemical sampling across different landscape units, including a headwater spring, an agricultural depression, and the catchment outlet. The results reveal contrasting hydrological response patterns and spatiotemporal hydrochemical dynamics, allowing the authors to distinguish between natural controls and human-induced (agricultural) influences on the karst system.

In addition, several studies set up the monitoring network to calibrate and test numerical hydrological models. Sarrazin et al. (2018) conducted measurements of precipitation, evapotranspiration parameters and soil moisture at 30-minute intervals at 4 plot locations in different countries with different climate and vegetation characteristics to test the V2Karst model. Vilhar & Simončič (2012) additionally measured throughfall and used the data obtained to calibrate the BROOK90 hydrological model. A comprehensive monitoring network was set up by Zhang et al. (2011) in a catchment area of a small karst spring. Vegetation and soil properties were determined by field studies and laboratory analyses, and the structure of the epikarst zone was measured using ground penetrating radar. To monitor recharge dynamics, three meteorological stations were established in areas with different vegetation types to measure precipitation and meteorological parameters. A series of soil moisture probes and rain gauges collecting throughfall were installed at each site. The water level was recorded at the outlet of the catchment area. All data obtained were used to calibrate and verify a distributed hydrology-soil-vegetation model. Although the models presented above allow simulation of recharge, the established monitoring networks did not provide the opportunity to test them against the measured flows in the karst aquifers.

Several studies aimed to identify subsurface flow regimes. Dasgupta et al. (2006) dug a trench in the soil and the upper part of a karst rock and measured the dynamics of water content at different depths after simulated rainfall events. Precipitation, throughfall, stemflow and surface runoff were measured on the tree-covered surface. Fu et al. (2015) constructed a trench perpendicular to the slope and measured subsurface flow in different parts of the soil-epikarst system after simulated rainfall events. In both experiments, the lower part of the vadose zone and the groundwater flow were not monitored.

Water flow regulation in the unsaturated zone of karst systems has been studied by integrating geophysical techniques with hydrological monitoring of soil moisture or cave drip hydrographs. This method reveals how water is stored and transmitted from rainfall to deeper karst conduits (Carrière et al. 2016; Poulain et al. 2018). On the other hand, observations of vadose flow in caves include monitoring of drip water and its dynamics generated by precipitation events (Kogovšek 2010;

Faimon et al. 2016; Baker et al. 2020; Baker et al. 2024; Baker et al. 2021; Nava-Fernandez et al. 2020; Liu et al. 2021) but lack monitoring of the effects of processes in vegetation and soil, which have an important influence on recharge. In a study by Jiang et al. (2025) observation was made how different parts of a karst aquifer system from surface soils to deep groundwater react as drought progresses. This study aims to fill an important gap by systematically observing every major hydrogeological compartment of the aquifer.

The current monitoring programs, e. g. the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects (ICP Forests, Schwärzel et al. 2022; ICP Waters, 2010) or Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research (eLTER, Ohnemus et al. 2024; Pipan & Aljančič 2024), etc., strive for an optimal observational design to enable confident scaling of local data to regional, continental or global scales. However, existing monitoring protocols are not sufficient to fully capture the complexity of environmental and socio-ecological systems in karst aquifers. Given the uniqueness of each karst aquifer, a standardized monitoring approach is challenging, yet clear guidelines remain essential.

The above examples show that the currently used monitoring systems lack a comprehensive coverage of the karst critical zone. Their shortcomings in terms of spatial and temporal representativeness limit their reliability in karst areas.

2.3. Monitoring strategy and rationale

This study focuses on the key components that influence water quantity and quality in karst areas by examining their interactions at the intersection of the atmosphere, lithosphere, pedosphere, hydrosphere, and biosphere. Specifically, we focused on precipitation regime, vegetation cover, soil, relief and rock properties, and underground water flow, along with their coupled effects. Our scope spans the vertical profile of a karst system—from the top of the forest canopy to the base of the groundwater saturated zone.

Karst, forming on carbonate and evaporate rocks due to their high solubility, results in pronounced permeability, unique landforms, soil and vegetation heterogeneity and a distinctive karst hydrology (Ford & Williams 2007). Karst hydrology features triple- porosity systems (the rock matrix, the fissures and the channels) and allows rapid groundwater infiltration. The fast and turbulent groundwater flow through heterogeneous pathways towards springs, coupled with storage in less permeable areas, leads to complexity of underground flow with potential transport over long distances (Bakalowicz 2005). Changing short- or long-term environmental conditions have a significant impact on the contaminant transport through karst aquifers and thus influence water quality (Hartmann et al. 2014; Covington et al. 2023; Ćuk Đurović et al. 2022).

Therefore, karst environments present unique challenges for ecohydrological monitoring due to their highly variable and site-specific processes, which differ significantly from those in non-karstic settings. Addressing this complexity requires a tailored, multi-scale, and interdisciplinary monitoring strategy. In the following section, we outline the rationale and key components of such a strategy, structured around the main challenges specific to karst systems.

i.) Why Ecohydrogeological Monitoring Matters.

The pursuit of ecohydrogeological monitoring in karst terrains is driven by a multifaceted set of objectives. Firstly, it is important to capture and interpret the signals of natural variability at different spatial and temporal scales. Such efforts are crucial not only for describing and predicting recharge conditions and water and mass fluxes, but also for deciphering the intricate feedback loops between different environmental spheres, such as vegetation influencing evapotranspiration and infiltration, or reduced recharge leading to lower dilution capacity, increased vulnerability to pollution, and potential loss of biodiversity (Stevanović et al. 2024). This understanding forms the basis for predicting the consequences of human interactions with these sensitive ecosystems and for testing different scenarios under changing environmental conditions.

ii.) Where to Monitor Addressing Spatial Variability in Ecohydrogeology.

Ecohydrogeological monitoring in karst terrains should comprise the vertical profile from the vegetation canopy to the saturated zone and springs. Determining the optimal locations presents a complex challenge, primarily due to the inherent KCZ vertical stratification and heterogeneity. The selection of monitoring sites is highly influenced by a range of factors, including the diversity of geology, topography, vegetation types — particularly canopy and root systems — and soil characteristics. These factors not only determine water infiltration into karst systems but also act as natural filters that moderate water flow and quality and therefore need to be monitored.

In particular, forest inventory programs worldwide are typically conducted at the plot level, using controlled experimental settings with permanent forest plots ranging from 0.5 to 1 ha that are remeasured over time (Bechtold & Patterson 2005; Ferretti & Fischer 2013). Ground vegetation and soil inventories, on the other hand, are usually conducted at the so-called micro-site level, and cover areas of 1 to 10 m^2 to account for spatial variations and reduce uncertainty. To ensure consistency, it is recommended to follow the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) methodology for ground vegetation monitoring (Canullo et al. 2020; Dobbertin et al. 2020) and soil sampling (Cools & De Vos 2020), taking into account the harmonized sampling, assessment, monitoring and analyses on the European level and beyond.

Geological and geomorphological mapping is carried out at various scales, from regional (1:50,000) to local (1:5,000), depending on the level of detail required. There is no standardized global protocol for geological and geomorphological mapping. However, several international organizations and national geological surveys provide widely accepted standards and frameworks (e.g. Remane et al. 1996; Gustavsson et al. 2006; INSPIRE Infrastructure for Spatial Information in Europe, 2024).

Detailed structural mapping in scales 1:5,000 or 1:10,000 is useful because all structural elements, which include tectonic elements as well as bedding planes, lithological changes, lithological partings, less permeable or impermeable interbeds, direct both vertical percolation and horizontal water flow within the karst and influence the frequency, size, spatial distribution, and shape of interconnected karst voids (Čar, 2018, Szczygieł et al. 2022: Šebela & Novak 2023). In karst areas, mapping is carried out both on the surface and underground, where speleological mapping is essential for documenting caves, conduits, and hydrological connections (Häuselmann 2002). This integrated approach enables a comprehensive understanding of karst systems, which is particularly important when studying the underground environment. Here the complexity of water flow is further enhanced by the variability of topography, geology, epikarst (weathered upper rock layer; Willimas, 2008; Polk et al. 2021), unsaturated (including cave systems) and saturated zones. These features strongly influence the spatial distribution of hydrological responses, making it essential to tailor monitoring efforts to different spatial scales. The interaction of water, energy and mass flow within these systems is particularly variable, as they can interact with surface flow paths, reinforcing the need for data collection strategies that account for this heterogeneity at both local and catchment scales. Hydrological monitoring should be carried out in strategically selected locations, i.e. critical recharge/discharge zones, to ensure comprehensive assessment and management of water resources (OJ EC 2000). It should follow internationally recognized guidelines, such as the WMO Guide to Hydrological Practices (WMO, 2008), ISO 5667–1 Water Quality Sampling Standards (ISO 5667–1, 2023) or USGS Manual (USGS, 2006), to ensure the accuracy, consistency and comparability of hydrological data. Despite the obstacles, karst springs often prove to be critical windows into the integrated behaviour of the hydrogeologic system and often provide the only source of information (Quinlan 1989). Wherever possible, attention should also be paid to monitoring sinking rivers, cave drips, and cave streams (Kogovšek 2010). These features can offer invaluable insights into aquifer behaviour, including recharge dynamics and more detailed, spatially resolved information.

iii.) What to Monitor? Essential Processes and Parameters.

Precipitation is the main source of recharge and monitoring should provide information on its amount, intensity as well as its spatial and temporal distribution (WMO, 2023; Goldscheider & Drew 2007). Vegetation cover determines precipitation interception and has an important influence on evapotranspiration. To quantify these processes, vegetation structure (horizontal and vertical) as well as composition (species level and abundance, habitats, communities), vegetation aboveground and belowground biomass, vegetation phenology and leaf area index should be monitored (Koch et al. 2009). Field measurements of precipitation, throughfall and stemflow help us to determine precipitation interception. Atmospheric parameters (e.g. wind speed and direction, relative air humidity and air temperature, wet and dry atmospheric deposition, solar radiation) also have an important influence on recharge and other ecohydrological processes (Raspe et al. 2020; Pörtner et al. 2022).

Snowfall as a special form of precipitation is temporarily stored water as snow cover on the surface and infiltrates into the soil with a certain time delay under favourable conditions with the melting process (Raspe et al. 2020; Ismail et al. 2023). In addition to the distribution and thickness of the snow cover and the density of the snow, this process is also influenced by the atmospheric and vegetation parameters mentioned above.

Due to its properties and interactions with water, the soil plays a decisive role in infiltration into the ground. In some karst areas soils are either thin or non-existent, which means that water storage and nutrient cycling are limited to the area between the epikarst (Geekiyanage et al., 2019) and the vegetation (Vilhar et al. 2005). Furthermore, in such highly porous hydrogeological terrain, areas with intact soil and vegetation cover are important for filtering, buffering, abiotic and biotic transformation of nutrients and pollutants and storage of plant-available water (Katzensteiner 2003; Clarke et al. 2022; ICOS, 2022). The soil inventory includes determination and the distribution of soil types and horizon thicknesses. At a minimum, soil porosity, rock fragment content and soil texture, the three most important soil properties that significantly influence soil moisture, should be additionally characterised (Fu et al. 2016). Furthermore, soil moisture and temperature should be monitored as well as the chemical properties of soils and the soil solution should be analysed (ICP Integrated monitoring, 2022).

In karst regions experimental approaches to determine fluxes are hardly possible, mainly because water pathways are hard to detect or remain unknown, and soil water infiltration can only be assessed using water balance approaches with different models (e.g. Watbal, BROOK90; Vilhar et al. 2010; Hammel & Kennel 2001; Federer et al. 2003).

For the characterization of flow paths in the unsaturated zone of the aquifer, information on detailed geomorphological and structural-lithological mapping at the surface and in caves is useful. Monitoring of water percolating into caves is facilitated by the observation of drips and the ponds formed by these drips. Typically, the discharge or water level, temperature and electrical conductivity of the water are measured. These parameters are also measured in cave streams and on the surface in sinking streams and springs, which are an input and output component of the karst hydrological system (Goldscheider & Drew 2007). Once installed, most data loggers in addition provide measurements of turbidity or particle size distribution, fluorescence and various other environmental parameters (Taylor & Greene 2008; Frank et al. 2018). These can play the role of processes indicators or surrogate parameters of contamination (Ravbar et al. 2023; Fernández-Ortega et al. 2024). On the other hand, traditional on-site sampling and laboratory work are still required for additional physical, chemical and microbiological analyses of specific parameters.

iv.) When to Monitor? A Temporal Variability Perspective.

Geomorphological, structural-lithological mapping and assessment of soil properties are usually one-off field campaigns. However, meteorological and hydrological variables or processes are monitored continuously or event based. With continuous monitoring, data is collected at regular intervals so that a constant flow of information is created over time. This method is particularly valuable with the advent of new technologies that allow measurements with high time resolution. Event-based monitoring, on the other hand, is used for targeted investigations or when significant changes are expected. It is used when focusing on multiple parameters or when monitoring certain variables that cannot be observed continuously.

The "space-for-time substitution" approach, which assumes that spatial and temporal variations are equivalent and derives a temporal trend from the study of sites of different ages (Pickett 1989), is often used in ecological studies for practical reasons. However, it may be unsuitable for studying environmental change in karst aquifers, as long-term studies are required to capture transient effects (Wogan & Wang 2018). When planning monitoring efforts to understand infiltration and recharge processes, it is crucial to take into account the temporal variations in throughfall and evapotranspiration resulting from seasonal vegetation changes. To capture whole range of ground vegetation changes on an annual basis, species abundance, composition and diversity need to be monitored in at least two sampling campaigns – i.e. in spring and in summer. Similarly, understanding vegetation phenology is crucial as it has a significant impact on net primary productivity and annual water and carbon cycles in terrestrial ecosystems (Davi et al. 2006; Piao et al. 2007). The phenological development of trees (Koch et al. 2009) or the leaf area index (leaf flushing, autumn leaf colouring, leaf fall, etc.) is recommended to monitor either event-based or continuously (Niu et al. 2021).

Due to the rapid flow rates and temporal variability encountered in karst aquifers, occassional water quality monitoring has been shown to be insufficient. More frequent monitoring, such as continuous and event-based monitoring with a resolution of few hours or half an hour, is more advisable compared to the less frequent options of weekly, monthly, quarterly, semi-annual or annual monitoring (Stevanović & Stevanović 2021).

v.) Who Should Carry Out Ecohydrogeological Monitoring?

The interdisciplinary nature of ecohydrological monitoring in karst emphasises the need for collaboration between different scientific disciplines (Vilhar et al. 2022). From vegetation science, forest ecology to karstology, geomorphology, hydrogeology and beyond, an integrated approach is essential for a holistic understanding of KCZ. Such collaborative efforts ensure comprehensive research into the individual and combined effects of different factors on ecohydrogeological processes in these complex landscapes.

3. Optimization of monitoring in a karst critical zone

To illustrate the proposed strategy, a case study was conducted in a forested karst aquifer that is part of the eLTER research network and the European LifeWatch research infrastructure (Pipan et al. 2018). This site is at the forefront of testing new monitoring methods and research innovations and was therefore selected as a case site to assess the strengths and limitations of the proposed monitoring system. This site was also chosen because it most closely aligns with the methodological criteria we argue are necessary for effective ecohydrological monitoring in karst environments. It provides a valuable example for illustrating the application of the proposed monitoring strategies and addressing the challenges identified in the review.

After site presentation, we here describe in detail the existing data collection methods to be able to assess how well these methods capture the spatial and temporal variability that is crucial for accurate monitoring of karst ecosystems.

3.1. Site description

In the Postojna-Planina Karst area in southwestern Slovenia, we have established an exemplary of a comprehensive network of 21 monitoring sites, both on the surface and in the underground (Fig. 2). Located on the gentle slopes of the Javorniki Mountains at an altitude between 530 and 640 m, the surface monitoring sites extend over a karst landscape characterised by rounded hills and karst depressions, the so-called dolines. Stratigraphically, Jurassic and Cretaceous limestones predominate, which are highly karstified (Čar & Gospodarič 1984). Climatically, the study area is in the transition zone between the Mediterranean and Continental climate with an average annual air temperature of 9.3 °C and almost 1500 mm of precipitation (Peel et al. 2007). The limestone is generally covered by Rendzic Leptosol or Chromic Cambisols, that occur in patches (Grčman et al. 2015).

There is no flowing surface water, as the rivers draining non-carbonate rocks, sink underground and reappear in two springs. The underground streams flow through the Postojna-Planina cave system, which stretches over a length of around 30 km. The Postojna Cave represents the underground course of the Pivka sinking river. In the Planina Cave there is a unique underground confluence of the Pivka and Rak sinking rivers (Fig. 2b). Together they form the Unica Spring. The Rak sinking river also contributes water to the Malenščica Spring. All the groundwater flow connections were verified by tracer tests (Gabrovšek et al. 2010 and references therein).

The predominant forest type is the Dinaric silver fir–beech forest (*Omphalodo-Fagetum* s. lat. association). These mostly uneven-aged forests are dominated by European beech (*Fagus sylvatica* L.) and silver fir (*Abies alba* Mill.), with an artificially increased proportion of Norway spruce (*Picea abies* Karst.) and admixtures of various broadleaves (e.g. Acer *pseudoplatanus* L., *Fraxinus excelsior*, *Ulmus glabra* Huds.) at the Planina monitoring sites and at the Postojna monitoring sites with natural admixtures of more thermophilic tree species such as sessile oak (*Quercus petraea* (Matt.) Liebl.) and European hornbeam (*Carpinus betulus* L.). These forests were significantly damaged by various disturbance factors, starting with a large-scale ice storm in 2014, followed by

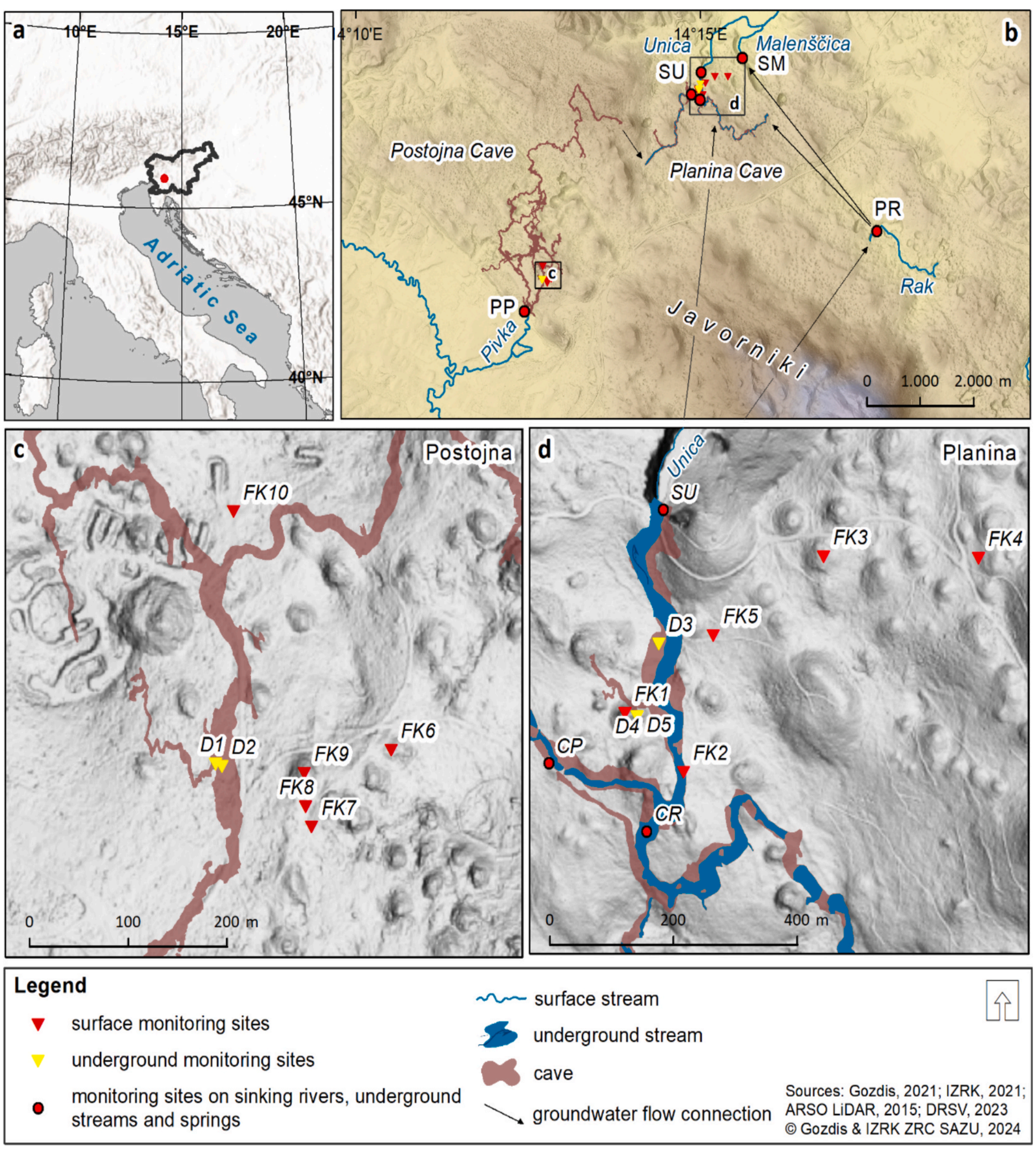

Fig. 2. Location of the Postojna-Planina Karst in southwestern Slovenia (a), surface and underground monitoring sites (b), with zoomed rectangles to monitoring sites at Postojna (c) and Planina (d). Surface monitoring sites are labelled FK1 – FK10, in the underground monitoring sites are labelled D1 – D5 in case of cave drips and streams. Labelling of the sinking rivers, underground streams and springs connected to the cave system is the following: ponor of the Pivka River – PP, ponor of the Rak River – PR, Pivka – CP and Rak channels of the Planina Cave – CR, Unica Spring – SU and Malenščica Spring – SM.

bark beetle outbreaks, windthrow and subsequent salvage logging, and the canopy gaps are now being overgrown (Nagel et al. 2016; Seidl et al. 2017; Kutnar et al. 2021).

3.2. Monitoring network and spatial variability perspective

In order to identify the main geological structures that determine the direction of flow of infiltrated water between the surface and the caves, a comprehensive one-time geomorphological and structural-geological mapping was done. A geomorphological field mapping on basis of surface digital elevation model made from airborne LiDAR data and a detailed structural geological field mapping at a scale of 1:5,000 according to Čar (2018) were carried out. The results were used to determine the lithology and geological structures, the strike and dip of the strata, the type and geometry of fractured zones (crushed, broken and fissured zones) including faults. Based on these results, we determined the monitoring sites on the surface and in the underground.

The study includes 10 surface (FK1 – FK10) and 11 underground (D1 – D5, PP, PR, CP, CR, SU and SM) monitoring sites. The 10 surface monitoring sites were strategically selected to represent key topographic karst features (dolines and interdoline areas), different forest development stages (canopy gap, regeneration and mature forest stands) and highly variable soil conditions (typically shallow or occuring in pockets). The setup includes two mature forest stand sites in dolinas and two in interdoline areas, two forest regeneration sites in dolinas and two in interdoline areas, and two large canopy gaps in interdoline areas – ensuring representativeness in heterogenous karst environment. To capture underground variability, two representative surface site combinations were established above the Planina and Postojna Caves. Each combination includes one mature forest stand site in a dolina and one in interdoline areas, one forest regeneration site in a dolina and one in an interdoline area, and one large canopy gap in an interdoline area.

In the underground, selected cave drips and streams D1-D5 differed due to geology, topography and in terms of water volumes and water flow characteristics. In order to compare the characteristics of the vadose zone with the general functioning of the observed aquifer, the points of its allogenic recharge (Pivka and Rak sinking streams), underground conduit flow (Pivka and Rak channels of the Planina Cave) and discharge (Malenščica and Unica springs) were also observed as monitoring points.

On the surface, we carried out a one-time detailed inventory of the vegetation types and species composition as well as the soil properties at plot level. All woody and herbaceous vascular plant species within a sample area of 10 x 10 m were recorded as part of a comprehensive vegetation inventory (Canullo et al. 2020). The abundance of the individual species was estimated using the standard phytosociological method according to Braun-Blanquet (1964). In addition, the percentage of the different vegetation layers was assessed: the tree layer, which includes trees and shrubs with a height of more than 5 m, the shrub layer, which includes all woody species with a height between 0.5 m and 5 m, and the herb layer (ground vegetation), which consists of all herbaceous plants and tree and shrub seedlings and saplings < 0.5 m in height.

Soil samples were taken from each plot according to the methodology described in Kobal et al. (2007). The organic horizons (subhorizons OL, OF and OH) and the mineral part of the soil were sampled in 10 cm depth increments down to bedrock. The organic part was sampled with a wooden frame, while the mineral part was sampled with a metal probe with an inner diameter of 6.7 cm. In each plot, five samples were systematically taken from each sub-horizon or depth and then combined into composite samples to reduce the influence of soil variability. In addition, the bulk density in the mineral part of the soil was measured at the same depths using Kopecky cylinders. The field capacity and permanent wilting point were determined using the retention curve method, where undisturbed soil samples were exposed to different pressures in the Richards extractor. Field capacity moisture was measured at a tension of –33 kPa and wilting point moisture at 1,500 kPa, with the values varying depending on the plant species. The difference in water content between the field capacity and the permanent wilting point gave the “available water content” for the surface monitoring sites. The soil texture was analysed in the Forest Ecology Laboratory at the Slovenian Forestry Institute and texture classes were determined by the proportion of sand, silt and clay particles in the mineral part of the soil according to ISO 11277 (ISO 11277, 2020).

3.3. Monitoring design addressing temporal variability perspective

At the surface monitoring sites we developed an innovative monitoring and sampling system for the continuous monitoring of precipitation (canopy gap) and throughfall (precipitation falling through the tree canopy), as well as air temperature, relative humidity, soil temperature and soil moisture content, which was used to assess canopy interception and atmospheric deposition (Fig. 3). The device consists of a HOBO RG3-M tipping bucket rain gauge connected to five plastic tubes with an outer diameter of 50 mm and a 10 mm wide and 1800 mm long notch. The tubes were connected to a special connector at the top of the tipping bucket rain gauge in the shape of a five-pointed star. Such a distribution of tubes allowed us to increase the sampling area of precipitation and throughfall, cover different conditions above the sampler installed in the forest and improve the representativeness of the measured precipitation and throughfall, especially in areas with heterogeneous forest vegetation (Žlindra et al. 2011).

Air temperature and relative humidity were monitored using a Sensirion SHT21 digital sensor housed in a seven-layer (130 mm diameter) solar shield. At large canopy gap sites, wind speed, wind direction and global solar radiation were monitored with Davis sensors to assess potential evaporation. Volumetric soil moisture content and soil temperature were monitored continuously at two depths (30 and 60 cm) using METER Group ECH2O EC-5 sensors. Due to the rocky terrain, the installation of the devices had to be adjusted to microscale conditions and sensors with a small detectable volume were required. DS18B20 digital thermometers from Maxim Integrated Products, Inc. were used to monitor soil temperature. All sensors were connected to the IoTminimForest data logger manufactured by the Laboratory of Electronic Devices, Slovenian Forestry Institute. Equipped with a cellular modem, each system transmitted data hourly to FTP server. The eEMIS platform, managed by the Slovenian Forestry Institute, collected the data and entered it into an SQL database, which has a user-friendly interface that allows regular check of the device status.

At the same monitoring sites, the leaf area index was measured from April to November in 2021, 2022 and 2023 using the LAI2200 Plant Canopy Analyzer to assess the vegetation phenology. These measurements were done weekly or bi-weekly, following a standardized protocol for tall canopies and forests (LAI-2200 2012). Large canopy gaps nearby were used as reference points.

In the underground, the continuous monitoring focused on the flow rate, water level, temperature, and electrical conductivity of cave drips (Fig. 3), sinking streams, underground streams and springs. Altogether we monitor five drips and streams within the Postojna-Planina cave system (D1 – D5). Another six monitoring sites are used to monitor sinking rivers, underground streams and springs connected to the cave system, i.e. PP – ponor of the Pivka River, PR – ponor of the Rak River, CP – Pivka and CR – Rak channels of the Planina Cave, SU – Unica Spring, SM – Malenščica Spring. To minimize environmental impact, our non-invasive monitoring systems were tailored to each point individually, considering microlocal characteristics of water flow and geomorphology. The dripping water in the caves was monitored using the Stalagmate drip counter (Driptych), which was placed in a funnel from which water was collected in a flow-through cup. Alternatively, Onset Hobo U20 divers were used to monitor the water level in the bowl below and the Hobo U24 was used to monitor temperature and electrical conductivity. Springs and streams were also logged using HOBO U20

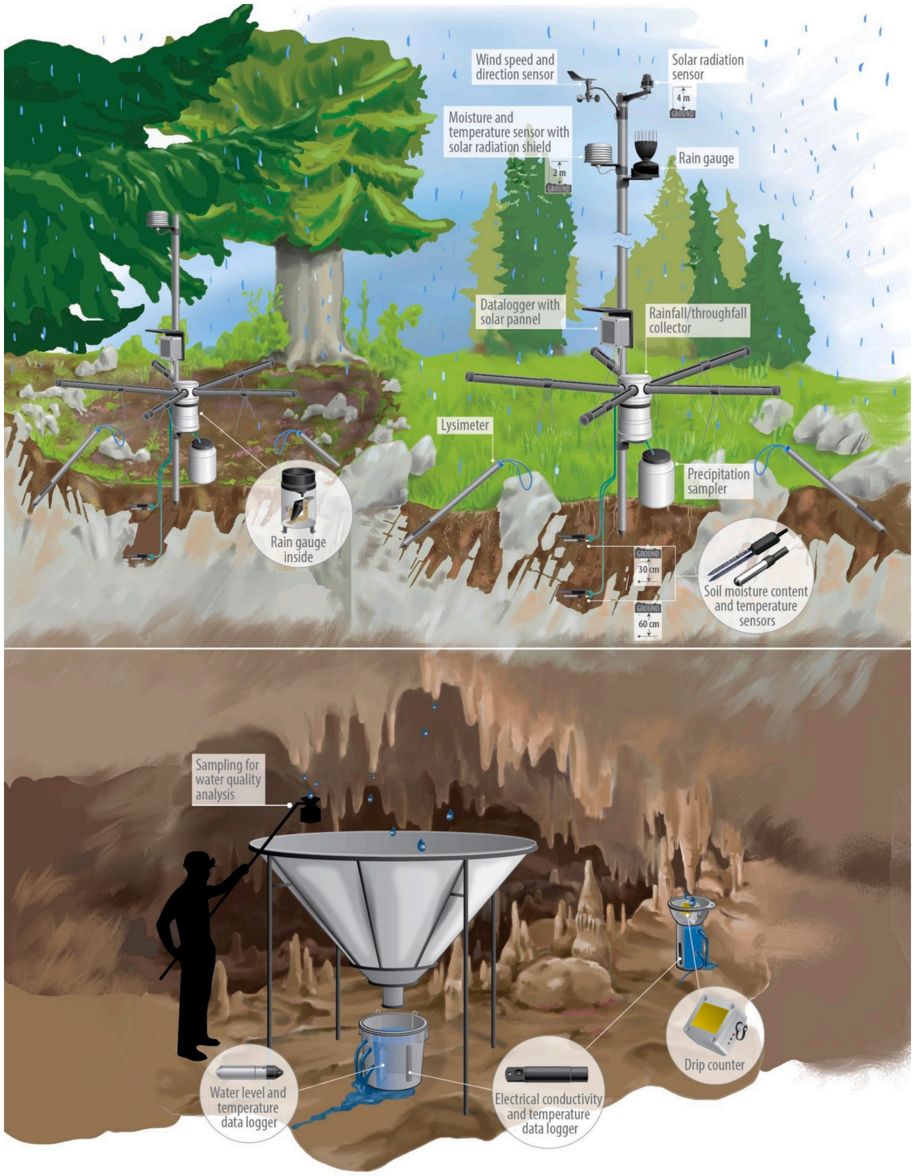

Fig. 3. Based on conceptual framework shown on Fig. 1 schematic representation of data integration is showing how surface measurements (e.g., precipitation and throughfall) are connected to underground observations (cave drips, and groundwater flow). The sketch is not to scale.

and U24. Stage-discharge relations of sinking rivers, cave streams, and springs were determined by taking occasional discharge measurements with SonTek's FlowTracker2 and RiverSurveyor M9, while we used a vessel and stopwatch at cave drip points. Discharges were determined based on these relationships and the water level or drip count measurements.

All continuous measurements are taking place in a time interval of 30 min since October 2020. Technical details of the monitoring devices are provided in Appendix. We ensure regular calibration of the instruments according to the principles of good practice and manufacturer's recommendation for each type of measurement separately.

3.4. Sampling strategies integration

In addition to the continuously measured parameters described in section 3.3., we closely monitored the transfer of soluble substances through the karst aquifer during and after autumn 2022 precipitation event, which took place between 25th September and 11th October. The aim of the sampling was to determine and monitor the transfer of natural tracers in the water through the KCZ.

For precipitation sampling (both canopy gap and throughfall), the connection between the installed monitoring system and the collection bucket below was used. As the zero-tension lysimeters used in the ICP Forests monitoring plots (Nieminen et al. 2016) are inadequate for soil solution sampling in shallow calcareous soils, innovative lysimeters were developed. In contrast to the porous ceramic lysimeters, which are installed horizontally, the newly developed gravity lysimeters are made of a stainless-steel tube with an inner diameter of 24.5 mm. A 500 mm cut-out allows soil solution samples to be taken from an area of approximately 85 cm^2 when inserted at a 45-degree angle. The water tank has a volume of approximately 500 cm^3 and is separated from the sampling section by a perforated sheet with a hole diameter of 1.25 mm, which is additionally protected with geotextile. The lysimeter was inserted into the soil using a drilling device with a 38 mm diameter drill bit. From the lysimeters soil solution was extracted via two plastic tubes with an internal diameter of 4 mm: one served as an exhaust air pipe for the air supply during pumping, the other was used for extracting soil solution via a membrane pump into an intermediate laboratory tank (Fig. 3).

The water sampling in the caves was based on taking water samples manually on site. At the time of the event described, only the cave drips and streams were sampled underground, as the focus of the research was on investigating solute transport in the unsaturated zone. In some earlier events, the sinking rivers, underground streams and springs were also sampled in a similar way, either manually or with portable samplers (Ćuk Đurović et al. 2022; Ravbar et al. 2023).

Sampling on the surface was done once a day, while sampling in the caves was done once or twice a day, depending on the amount of precipitation and dripping intensity or discharge. Water analyses were conducted in the Laboratory of Forest Ecology at the Slovenian Forestry Institute, focusing on nutrient concentrations in canopy gap precipitation, throughfall, soil solution and groundwater, including pH (Metrohm pH low ionic strenght electrode), electrical conductivity (Metrohm conductivity electrode Pt 1000), alkalinity (Metrohm 702 SM Titrino module), main anions (NO_3^-, NO_2^-, Cl^-, PO_4^{3-}, SO_4^{2-}; Metrohm ion chromatography modular system with Metrosep A SUPP 5 – 150/4.0 column), main cations (NH_4^+, Na^+, K^+, Mn^{2+}, Ca^{2+}, Mg^{2+}; Metrohm ion chromatography modular system with Metrosep C 4 – 150/4.0 column), total nitrogen and DOC (Shimadzu TOC-L and TNM-L instrument). Technical details of the laboratory devices are provided in Appendix.

4. Insights from monitoring

4.1. Spatial variability perspective

As we focus on the principles of KCZ monitoring and given the wealth of data obtained, we are only presenting selected results to illustrate and better understand the functioning of the established monitoring network and to underpin the need for a holistic approach to monitoring with the case study results. For example, the structural-lithological mapping above and in the Planina Cave revealed that dolomite and dolomite breccia intercalations occur between the predominant limestone. Characteristic fissure zones and strongly karstified fracture zones manifest themselves as karrenfields (Fig. 4). There are also many deep solution dolines in the area. The structural features on the surface as well in the cave below include significant Dinaric faults that may serve as main pathways for water flow. The monitoring points on the surface and in the cave were selected on the basis of these results, which provide insights into geological structure and possible water flow connections.

The vegetation inventory at the surface monitoring sites shows that the tree canopy covers 70 % or more, especially at the Planina sites, while at the Postojna sites two regeneration plots have a tree cover of 15 % (Fig. 5a). At the Planina sites, the shrub layer is more homogeneous and covers between 20 % and 50 %, while at the Postojna sites it varies greatly from plot to plot and is between 8 % and 70 %. These two vegetation layers are particularly important for precipitation interception, microclimatic conditions and light availability on the forest floor. Although there is a positive correlation (Spearman's rho: 0.62) between tree cover and the measured leaf area index (LAI; 3.1–9.2) in forest plots in 2022, LAI varies independently of vegetation type and geomorphologic form. In large canopy gaps plots, ground vegetation accounted for most of the total vegetation cover and the LAI was 0 (Fig. 5b). The selected areas show considerable differences, which is of crucial importance for the study of interception and evapotranspiration, as these processes are highly influenced by local environmental conditions.

The depths of organic horizons, including the subhorizons OL, OF and OH, are similar regardless of geomorphology (Fig. 5c). The depth of the mineral soils, on the other hand, shows greater variability, which can mainly be attributed to the geomorphological differences of the terrain. The mineral soils are deeper in the interdoline areas, while shallower soils are found on the slopes of the dolines or interdoline areas.

The soils are classified as silty clay loam soils, and their texture

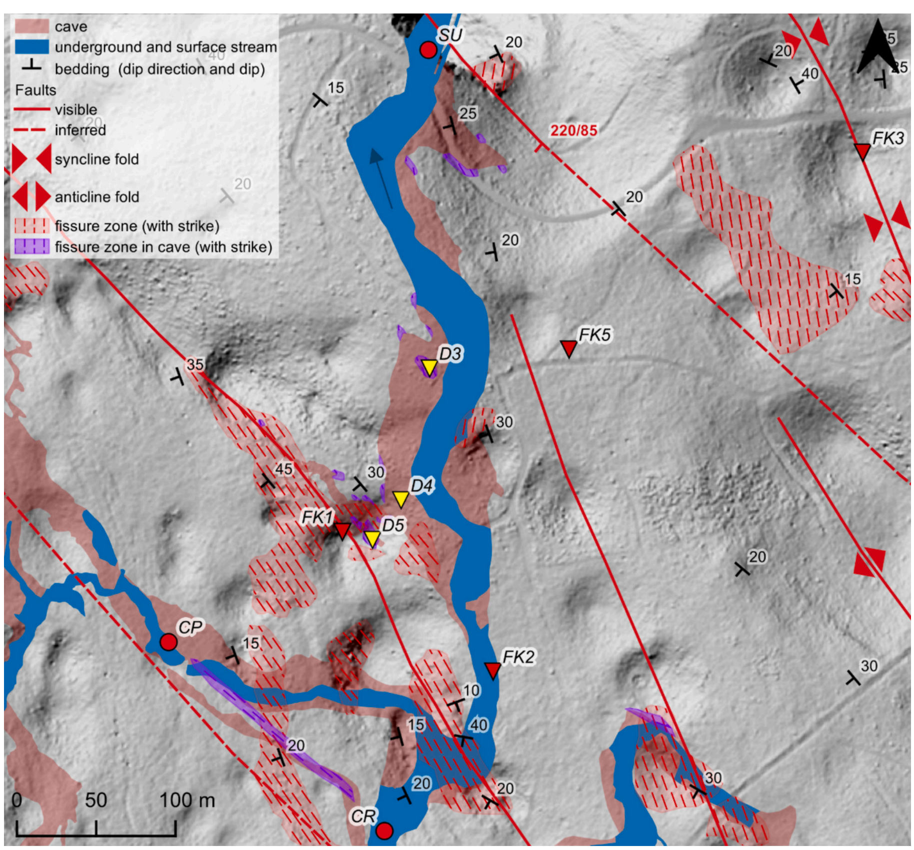

Fig. 4. The structural-geological map of the Planina area shows the predominant NW-SE trending Dinaric faults and the associated karstified structural features, emphasising their role in creating vertical connections and drainage paths between the surface and the underground. For location see Fig. 2.

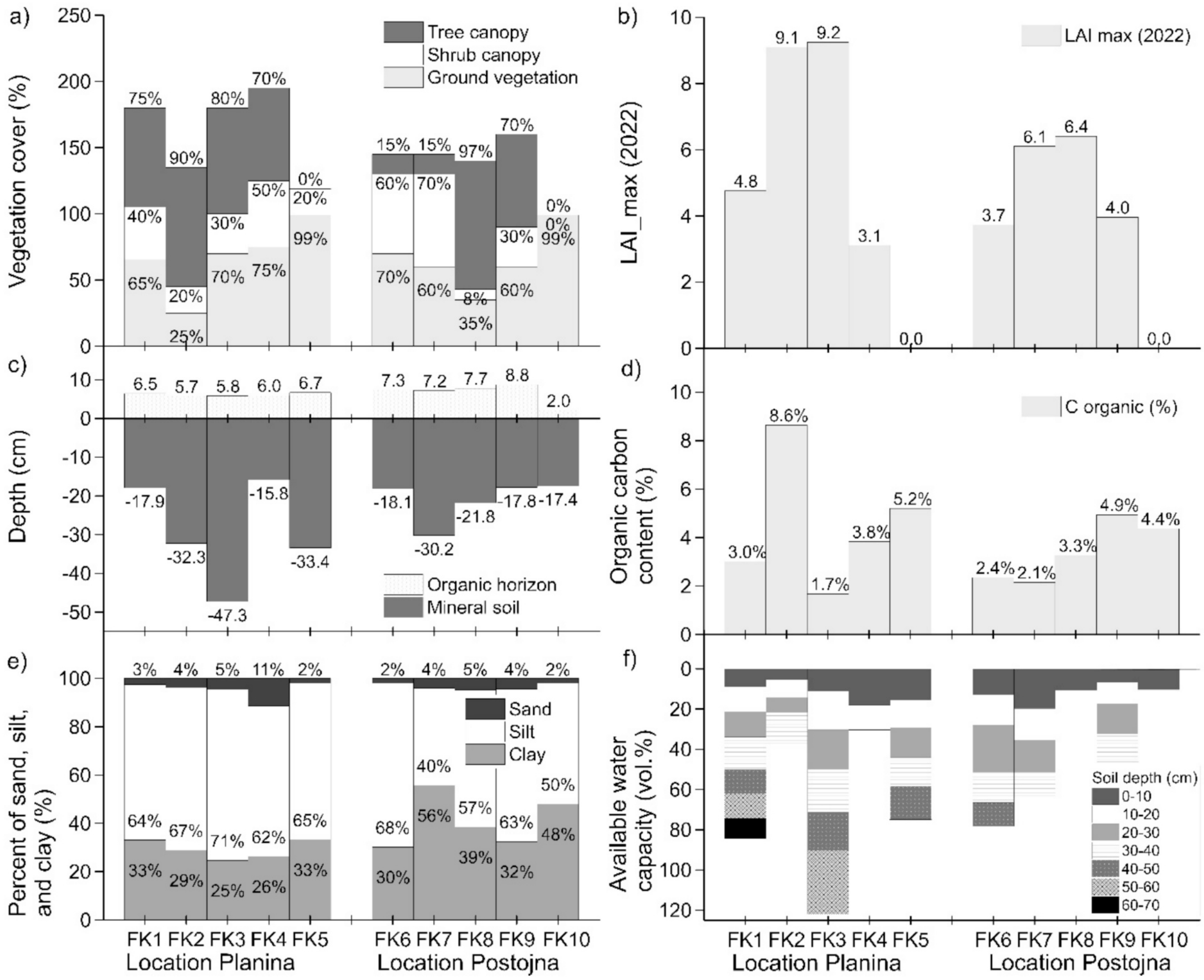

Fig. 5. A) estimated vegetation cover in three layers: tree (woody species > 5 m), shrub (0.5 m < woody species < 5 m) and ground vegetation (woody species < 0.5 m and all herbaceous plants); b) Maximum leaf area index (LAI max) in 2022; c) Depth of the organic horizon and mineral soils; d) Organic carbon content (%); e) Proportions of sand, silt and clay in soils; f) Available water capacity (vol. %) in soils at surface monitoring sites.

remains evenly distributed. Although some sites, such as FK7 and FK10, have a higher clay content, the sand content remains relatively uniform across all surface monitoring sites and does not exceed 11.5 % (Fig. 5e). This uniformity of soil properties increases the reliability of our monitoring and supports a comprehensive assessment of forest ecosystem dynamics and water retention. Despite some differences, the pattern of soil depth and texture is similar between the monitoring sites, facilitating comparisons across different forest development phases and precipitation conditions.

The available water content measures the amount of water that the soil can retain for plants through evapotranspiration and the amount that drains into the underground. It is achieved after gravity drainage of water from the macropores and typically occurs within 2–3 days after rainfall in uniformly structured, pervious soils (De Oliveira et al., 2015). At the surface monitoring sites this value varied widely, ranging from 122 vol% at FK3, which is located in a deeper doline with a high percentage of silt in soil and is covered by dense natural forest regeneration, to 10.7 vol% at FK8, which is located in a mature forest stand in the interdoline area. These differences are mainly due to geomorphological variations in the karst terrain, soil depth, soil texture and organic matter content described above and are therefore important for the study of infiltration and soil processes, which are particularly deficient.

4.2. Temporal variability perspective

To monitor the underground flow dynamics and transfer of soluble substances event-based monitoring was done in mid-September 2022, when after a severe drought, about 80 mm of rain fell initially and about 170 mm at the end of the month (Fig. 6). This was enough to saturate the soil and the unsaturated zone of the aquifer. Continuous monitoring, here presented in the examples of FK3 and FK5 monitoring sites, showed greater precipitation amount in the regeneration canopy gap (FK3) compared to large canopy gap (FK5). Other studies have also noted that during certain precipitation events, more concentrated precipitation falls in small canopy gaps compared to large ones, despite the significant influence of the forest stand edge. This is due to air turbulence within the small opening, which causes more rain to fall on the windward side, as well as the accumulation of raindrops on the leaves, which form larger droplets and the concentration of precipitation under the canopy (Krečmer 1967; Vilhar 2010).

In the large canopy gap, soil moisture is higher at a depth of 60 cm than at a depth of 30 cm, while the opposite is true in the regeneration canopy gap in a doline. The lower soil moisture content at 60 cm depth in the regeneration canopy gap can be attributed to intensive rooting and moisture consumption by young tree saplings in deeper soil layers as well as by neighboring trees whose roots extend into the gap (Baker et al. 2013). This also leads to a greater difference in soil moisture content between the shallower and deeper soil horizons in the regeneration

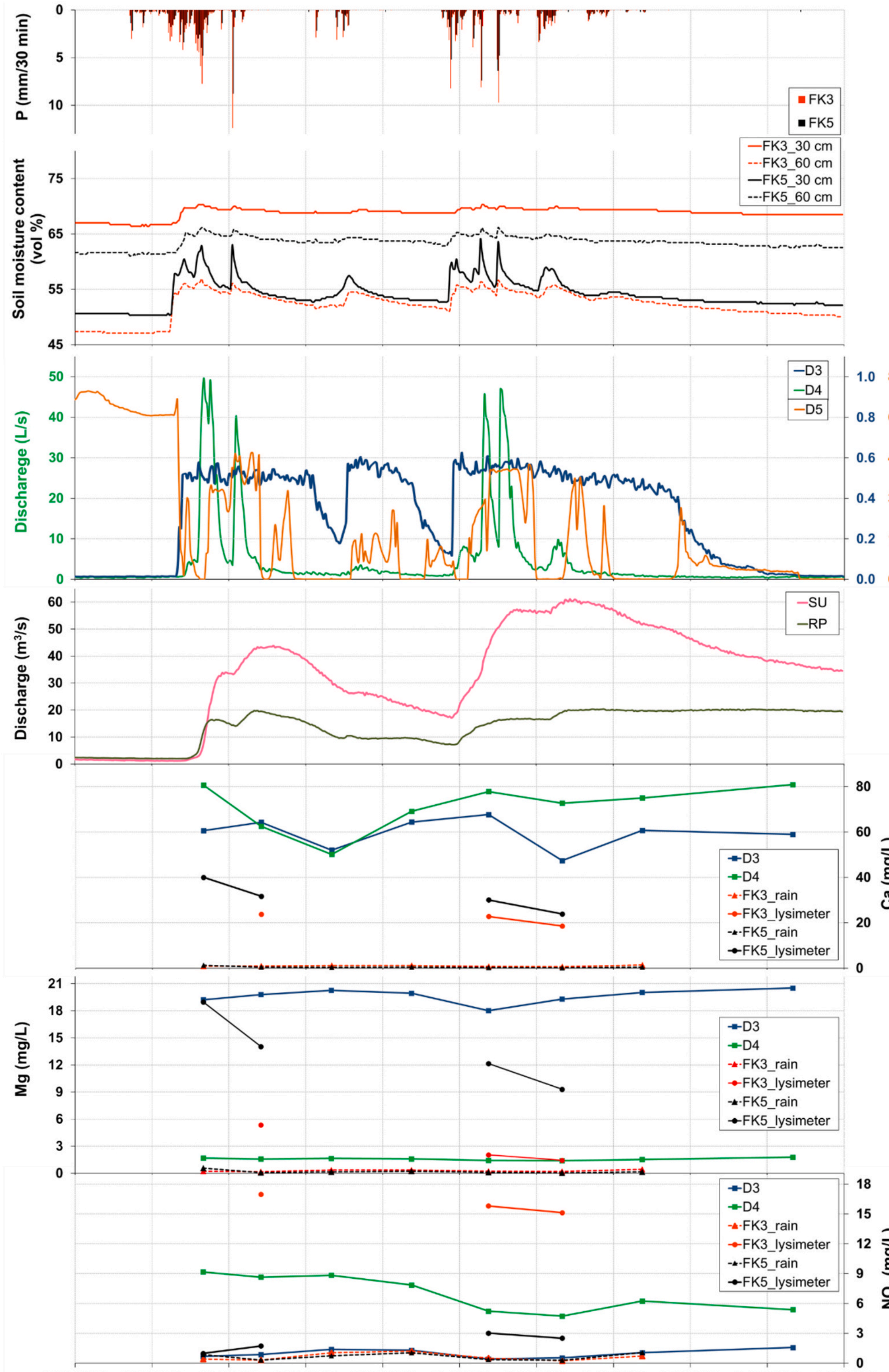

Fig. 6. Selected hydrological and chemical parameters before, during and after the rainfall in autumn 2022 at surface and underground monitoring sites.

canopy gap compared to the large canopy gap. For the herbs and grasses in the large canopy gap, most of the roots are located in the upper soil layers, resulting in greater fluctuations in soil moisture after rain events and a lower soil moisture content at 30 cm depth compared to 60 cm depth. In addition, soil evaporation in the large canopy gap dries out the shallower soil horizons further due to the stronger air turbulence, unlike in smaller canopy gaps (Lenk et al. 2024; Von Arx et al. 2013). This effect is not present in the regeneration canopy gap, as the canopies of young tree saplings provide shade (Vilhar and Simončič, 2012). After heavy rainfall, soil moisture in the large canopy gap increases significantly in the upper part of the soil (an hour after the most intensive rain) and with a half-hour delay at depth, while the opposite is the case in the soil in the regeneration canopy gap in a doline. This can be explained by the fact that the rainwater flows in a more concentrated form and via primary paths in the soil, e.g. along the rocks and roots.

These differences are very pronounced on the surface, but underground flow dynamics depend more on the drainage paths in the unsaturated zone, and the drips can behave very differently. The D3 drip reacted very quickly, with a delay of two hours after heavy rainfall. The behavior of the D5 drip could not be evaluated because it changed its direction when the flow rate increased and no longer flowed to the measuring device, which is reflected in the graph by the decrease in the flow rate values. Cave stream D4 took another two hours to react, but after 8 h, when the rain stopped, it declined sharply. In contrast, D3 maintained high drip rates for two days. In comparison, the Rak sinking River and the Unica Spring took six and four hours respectively to react after heavier rainfall. Due to the size and heterogeneity of the draining area, the increase and especially the decrease of their discharges is milder. The Unica reflects the great influence of the Rak. Similar behavior can be observed with further rainfall.

To illustrate the importance of monitoring natural tracers at different sites within a karst system, an example of the results of measurements of calcium and magnesium concentrations (carbonate-rock related parameters) and nitrate (soil-related parameter or pollution indicator) in precipitation (rain gauge), soil solution (lysimeter) and cave water is presented. Depending on data availability and due to significant differences, sites FK3 (regeneration canopy, doline) and FK5 (large canopy gap, interdoline area) were selected on the surface and sites D3 (cave drip) and D4 (cave stream) in the cave. The lack of results from the soil solution reflects the difficulty of obtaining samples with zero-tension lysimeters. We assume that more soil solution samples would be available during more abundant precipitation events. Furthermore, as the profile of the karst soil is not uniform and often consists of soil pockets between rocks and roots, infiltrating soil water can follow preferential flow paths and bypass the installed lysimeter. Consequently, dry periods and low-intensity rainfall events remain underrepresented, introducing seasonal data gaps and potential bias in the interpretation of soil–water processes.

The concentrations of selected parameters in precipitation under the canopy or in the large canopy gap vary only minimally, the values are low (around 1 mg l^{-1}). There is already a significant increase in calcium content in soils formed on limestone and dolomite. Clear differences between the two sites (19–24 mg l^{-1} in FK3 and 24–40 mg l^{-1} in FK5) are probably due to differences in lithology. The presence of dolomite in FK5 is indicated by higher magnesium concentrations (1.4–5.4 in FK3 and 9.3–19 mg l^{-1} in FK5). The further dissolution of the karst rock by the water flowing through the fissures in the unsaturated zone is reflected in an increase in the calcium concentrations (50–80 mg l^{-1} in D4 and 47–68 mg l^{-1} in D3). The magnesium levels (1.4–2.1 mg l^{-1} in D4 and 18–21 mg l^{-1} in D3) indicate a possible connection between the FK5 and D3 sites. When the hydrological conditions change after a rain event, the dilution by the new rainwater reduces the calcium and magnesium concentrations in the soils and rocks, as expected. Nitrate concentrations are significantly higher in FK3 (15–17 mg l^{-1}) than in FK5 (2.5–3 mg l^{-1}). The strong influence of local conditions and the heterogeneous karst structure is also evident in the differences between the two monitoring sites in the cave, with concentrations remaining very low in D3 (0.4–3 mg l^{-1}) and significantly higher in D4 (4.7–9.2 mg l^{-1}). These results confirm that a wide network of monitoring sites in different environmental compartments/spheres of the karst critical zone is required to understand the characteristics of solute transport through karst aquifers.

5. Discussion

5.1. Advancing ecohydrogeological monitoring in karst environments

The results presented indicate considerable variability and heterogeneity of natural conditions in karst areas. The patterns observed cannot be explained by the influence of just one or two factors, but rather by the interplay and interaction of several of them. Therefore, the novelty of the monitoring described lies in its multispheric approach, which is applied and justified within the framework of a proposed karst critical zone observatory. In contrast to conventional monitoring systems, which focus on isolated environmental components (White et al. 2015; Mollenhauer et al. 2018; Ohnemus et al. 2024), this approach integrates the atmosphere, biosphere, hydrosphere and geosphere, thus enabling a holistic monitoring of ecohydrological processes in karst environments. This interconnected perspective is essential to capture the complexity of karst systems, where interactions between climate, vegetation, soil, water, geology and geomorphology occur at multiple spatial and temporal scales. Furthermore, the integration of methods from karst research, hydrogeology, ecology and forestry science is crucial for the monitoring approach. This interdisciplinary monitoring framework ensures that all relevant factors influencing ecohydrological processes are considered, thus enabling a comprehensive understanding of the karst environment.

Given the unique characteristics of the karst area, all surface measurements have been carefully designed to take into account the complexity of the landscape, which was given a low priority in previous studies (e.g. Bottrell & Atkinson, 1992; Zhang et al. 2011; Heilman et al. 2012; Baker et al. 2020; Schwärzel et al. 2022). The monitoring design takes into account topographic variations, rocky surfaces, heterogeneous vegetation and soil cover, that influence the methods of data collection in different environmental spheres. To ensure representativeness, geological and geomorphological mapping, vegetation and soil inventories were carried out. In this way, the monitoring network was spread across multiple plots to capture the inherent diversity of the karst environment. It consists of ten surface monitoring sites strategically selected to capture key topographic karst features, different microclimatic conditions, vegetation and soil types. Topography was taken into account by including doline and interdoline areas, and vegetation by the different forest types and development stages, including canopy gaps, natural forest regeneration and mature forest stands. For this reason, a comprehensive vegetation inventory was conducted in more detail than usual in terms of horizontal and vertical diversity. In addition, this spatially extensive monitoring network required special care in the placement of soil temperature and moisture sensors, as soil conditions vary widely, ranging from bare limestone outcrops to the accumulation of organic matter in soil pockets, cracks and crevices to soils with high stone content. The installation of the devices had to be adjusted to microscale conditions.

Underground monitoring points are inherently karst-specific. What applies to the surface has also been considered for the underground monitoring sites, which are strategically selected according to hydrogeological characteristics, including swallow holes, caves and springs. The installation of the monitoring equipment was carefully adapted to site-specific conditions to ensure reliable data collection. Loggers were placed in swallow holes to capture infiltration dynamics and rapid recharge processes. In caves, sensors were positioned to monitor underground flow paths and water level fluctuations, taking into account the complex morphology and limited accessibility. At springs, discharge fluctuations and other properties are monitored, that reflect upstream hydrological processes. The monitoring devices are of different types and those best suited to the specific needs of each site have been selected to ensure optimal functionality. The installation of the devices was tailored to the specific conditions of each site to overcome the challenges of the karst terrain.

The spatial extent consideration allowed for a more comprehensive assessment of environmental processes, as conditions can vary greatly even over short distances due to microtopographic effects and subsurface heterogeneity. Only by diversifying the monitoring points and observing the entire profile can we capture the characteristics of the KCZ as a whole. Such monitoring is also crucial for quantifying groundwater recharge and pollutant transport.

In order to detect significant fluctuations in conditions even within short distances, some monitoring methods and techniques had to be adapted. For example, atmospheric parameters are measured with adapted techniques that take into account the irregular karst topography and canopy cover to improve the representativeness of precipitation and throughfall. The highly diverse nature of soils requires a tailored moisture content and temperature sensors with smaller detectable volume, as well as adapted sampling strategy for soil solution sampling using gravity lysimeters. While they are effective in areas with stable connections, cellular data loggers in remote forested areas or closed relief forms (e.g. pocket valleys, collapse dolines) face the problem of weak signals which require more energy for data transmission and lead to possible battery drainage. This approach is not practicable in caves as there are no signals, which makes real-time data transmission impossible. Regular maintenance is required to correct malfunctions caused by litter, calcite deposits, or damage caused by flooding and wildlife in forests and caves.

Table 1 summarizes the proposed adaptations and innovations in the monitoring program for the karst critical zone (KCZ), in comparison to standard approaches. These adjustments account for the pronounced variability and heterogeneity of karst environments and support a more holistic observation of ecohydrological processes. While the full set of measurements is not always required or possible for every application, the monitoring design is flexible and can be adapted to the specific goals of individual studies. By combining site-specific methodological adaptations with a broad, multidisciplinary approach, this monitoring system provides a more robust basis for understanding and managing karst ecosystems. In addition to environmental spheres addressed in this study, socio-economic aspects are also monitored as part of eLTER (Ohnemus et al. 2022). Here, we have not dealt with them separately, as they are covered in other studies, such as annual forest increment (m^3 ha^{-1}) (Slovenia Forest Service), tourist visits to caves (Šebela 2021) and changes in vegetation and land cover (Ravbar et al. 2024).

5.2. Evaluation of the monitoring network

The proposed monitoring approach has proven to be crucial for capturing a wide range of variables and integrating cross-disciplinary methods to enable observation of intricate interactions and the complexity of ecosystem dynamics, especially in highly heterogeneous karst terrains. This holistic perspective is essential for accurate data collection and the perception of change. After designing and implementing the proposed monitoring and analyzing the results, we were able to assess the strengths, weaknesses, limitations and opportunities of the established monitoring network in a forested karst aquifer. The findings are summarized in Table 2, divided into general findings applicable to various environments and karst-specific findings relevant to karst ecosystems.

i.) Strengths of the established monitoring approach

- Comprehensive coverage of the KCZ spheres: the selected variables encompass various observable spheres of the critical zone, offering a balanced combination of scientific relevance, implementation ease, and cost-effectiveness.
- Spatio-temporal perspective: the monitoring network effectively captures both spatial and temporal variations and provides comprehensive monitoring of dynamic ecohydrological processes in different karst landscapes and at different time scales, ensuring comprehensive data representation and robust analysis.
- Integration of interdisciplinary expertise: advanced monitoring program benefits from collaboration and knowledge sharing between different disciplines and professionals who have a wealth of experience in applying a wide range of traditional direct and indirect monitoring techniques, ensuring innovative and comprehensive approach to data collection and analysis.
- Development of customized monitoring solutions: the study case required site-specific design, testing, and implementation of monitoring systems tailored specifically for karst research that could be transferred to other similar karst areas. This includes the development of automatic or semi-automatic instruments optimized for karst environments and adjusted to microscale conditions.
- Enhanced precipitation monitoring: through the utilization of a specially designed advanced precipitation monitoring system, we have significantly increased the sampling area by 4.8 times from 182.4 cm^2 (standard HOBO RG3-M tipping bucket rain gauge) to 875.5 cm^2. Instead of a single collector, the system uses five tubes arranged in a five-pointed star with a diameter of 400 cm. This expanded design improves the representativeness of precipitation and throughfall measurements, particularly in plots with heterogeneous forest vegetation.
- Technological innovation: The newly developed stainless-steel gravity lysimeters enable the precise extraction of soil solution from the soil. They have a water tank separated by a perforated sheet and are installed using a drilling device. The soil solution is extracted and collected via plastic tubes connected to a membrane pump.

ii.) Weaknesses of the established monitoring approach

- Spatial representativeness in forest inventory, soil surveys, geological and geomorphological assessments: the inherent heterogeneity of karst areas poses a challenge to the accurate data assessment. In forests it is difficult to assess deposition patterns with existing collectors, requiring a larger number of collectors per plot. The heterogeneous nature of karst soils, which often occur in pockets, is also difficult to assess. In addition, the geomorphology of the surface and subsurface in karst areas varies considerably, making the identification and assessment of underground water flow paths difficult. Addressing these challenges is critical to increase the spatial representativeness of monitoring efforts and improve the accuracy of assessments.
- Regular maintenance, cleaning and checking of measuring equipment are necessary to address issues such as equipment malfunction caused by e.g. litter accumulation in forest (leaves, needles, fruits, etc.) or calcite deposition in cave environments, battery depletion or damage from environmental factors like floods or wild animals.
- Suitability for snow precipitation: the gutters of precipitation monitoring equipment may not be suitable for snow precipitation due to narrow openings and lack of heating in winter, affecting the accuracy of measurements during snowy conditions.
- Constraints on lysimeter operation: lysimeters may face operational constraints due to soil-physical properties, such as limited capture area and difficulty in checking soil homogeneity after installation.
- Placement of loggers in caves: optimal placement of loggers in water caves is crucial for accurate water level recordings, especially during event conditions. Ensuring proper placement can be very challenging due to fluctuating water levels. Acoustic drop counters may face limitations in accurately measuring drop counts, particularly when drops fall from great heights and splash or combine into stronger jets during rainfall or snowmelt events causing unrealistic deviations in water flow records. Finding the optimal location for deployment of the loggers in caves is therefore crucial.
- Challenges with cellular dataloggers: although in areas with stable and robust cellular signals, use of cellular dataloggers ensures efficient data transmission, this approach is not applicable in closed depressions and cave environments where cellular signals are often unreliable or absent. In areas with low cellular signal, cellular dataloggers require more power for data transmission, leading to potential battery drain. Cellular data transmission from caves can be demanding and costly, further complicating monitoring efforts.

Table 1
Suggested adaptations and novelties in observation program of the karst critical zone (KCZ), compared to standard observations.

<table>
<tr><th>KCZ sphere</th><th>Standard observations</th><th>Standard protocol</th><th>Peculiarities / Challenges in karst areas</th><th>Suggested adaptations and novelties in observation program of the KCZ</th></tr>
<tr><td>Atmosphere</td><td>Continuous measurements of meteorological data, such as open field precipitation, air temperature, relative air humidity and global radiation (incoming and reflected)</td><td>ICP Forests (Raspe et al. 2020); in accordance with WMO (2008); ICOS (2022)</td><td rowspan="7">Specific karst topographic features (dolines, interdoline areas)
→ INTERLINKED WITH GEOSPHERE

Air temperature turnover in karst depressions
→ INTERLINKED WITH GEOSPHERE

High variability of vegetation types and very heterogenous forest structure and composition – forest development stages (canopy gap, regeneration, mature forest stands) in small area
Specific and extremely heterogenous soil conditions
(e. g. bare limestone rocks at the soil surface, organic matter accumulated in cracks and holes, high stone content in soils, etc.)
→ INTERLINKED WITH GEOSPHERE

High variation in spatial and temporal atmospheric deposition in small area
→ INTERLINKED WITH HYDROSPHERE</td><td>Multiple spatially distributed and diverse surface automated weather stations</td></tr>
<tr><td></td><td>Atmospheric deposition (open field precipitation, throughfall and stemflow) chemical analyses → INTERLINKED WITH HYDROSPHERE</td><td>ICP Forests (Raspe et al. 2020, Clarke et al. 2022)</td><td>Higher number of open field precipitation and throughfall collectors with larger sampling area;
An innovative monitoring and sampling system for the continuous monitoring of open field precipitation and throughfall</td></tr>
<tr><td></td><td>Continuous measurements of soil temperature and moisture content
→ INTERLINKED WITH GEOSPHERE</td><td>ICP Forests (Raspe et al. 2020); in accordance with WMO (2008); ICOS (2022)</td><td>Multiple surface monitoring sites with volumetric soil moisture content and soil temperature sensors;
Sensors with a small detection volume needed to monitor soil moisture and temperature in rocky karst terrain</td></tr>
<tr><td>Biosphere</td><td>Vegetation composition:
– Inventory of the vegetation types and species composition – woody and herbaceous vascular plant species
– The abundance of the individual species
– The percentage of the different vegetation layers: tree, shrub herb layer (ground vegetation)
→ INTERLINKED WITH GEOSPHERE</td><td>ICP Forests (Canullo et al. 2020; Dobbertin et al. 2020; Braun-Blanquet 1964)</td><td>Higher number of vegetation inventory micro-sites</td></tr>
<tr><td></td><td>Vegetation phenology and Leaf Area Index (LAI): start, maximum, end of season</td><td>ICOS (2022); ICP Forests (Raspe et al. 2020); LAI-2200 (2012).</td><td>Higher number of tree phenology monitoring sites</td></tr>
<tr><td>Geosphere</td><td>Soil inventory: Standard soil physical and chemical parameters
(e. g. soil type classification, texture, particle size distribution, pH, CEC and BS, soil bulk density, soil organic matter, soil water holding capacity (pF curve, field capacity, permanent wilting point, plant available water)</td><td>ICOS (2022); ICP Integrated Monitoring (2022); ICP Forests (Cools & De Vos 2020); ICP Integrated monitoring (2022) ; ISO 11277 (2020)</td><td>Higher number of soil inventory micro-sites (small-scale adaptive monitoring)</td></tr>
<tr><td></td><td>Soil water chemical characteristics:
→ INTERLINKED WITH HYDROSPHERE
→ INTERLINKED WITH BIOSPHERE</td><td>ICP Forests (Nieminen et al. 2016), ICP Integrated Monitoring (2022)</td><td>Higher number of soil solution monitoring sites;
Using newly developed gravity lysimeters</td></tr>
<tr><td></td><td>Geomorphological features
Geological site characterization (determination of the lithology and geological structures)
→ INTERLINKED WITH HYDROSPHERE</td><td>International Commission on Stratigraphy (Remane et al. 1996); INSPIRE Infrastructure for Spatial Information in Europe (2024); Gustavsson et al. 2006</td><td>Specific surface karst features influencing recharge (infiltration)
Karst caves with access to groundwater flow
Heterogeneous structure with triple porosity</td><td>A geomorphological field mapping on basis of surface DEM made from airborne LiDAR data;
Speleological mapping (Häuselmann 2002);
A detailed structural geological field mapping according to Car (2018) on the surface and in caves – the type and geometry of fractured zones (crushed, broken and fissured zones) and their influence on groundwater flow.</td></tr>
<tr><td>Hydrosphere</td><td>Groundwater flow
→ INTERLINKED WITH GEOSPHERE
Groundwater quality
→ INTERLINKED WITH ATMOSPHERE</td><td>Water Framework Directive (OJ EC 2000); WMO Guide to Hydrological Practices (2008); ISO 5667 Water Quality Sampling Standards (2023); USGS National Field Manual for the Collection of Water-Quality Data (2006)</td><td>Dynamic exchange between surface flow and groundwater flow;
High variability of flow rates;
High variability of water quality influenced by hydrological conditions</td><td>Measurements and sampling in sinking streams, water caves (drips, ponds, streams) and springs;
Continuous monitoring of physical and chemical parameters;
Non-invasive monitoring systems tailored to each point individually;
Event-based instead of regular water sampling;
Physical, chemical and microbiological analysis of specific parameters</td></tr>
</table>

Table 2
Summary of the evaluation of the monitoring network and division into general and karst-specific findings.

Evaluation of the monitoring network		
i.) Strengths of the established monitoring approach	General	Karst-specific
Comprehensive coverage of the KCZ spheres		✔
Spatio-temporal perspective		✔
Integration of interdisciplinary expertise	✔	
Development of customized monitoring solutions		✔
Enhanced precipitation monitoring	✔	
Technological innovation		✔
ii.) Weaknesses of the established monitoring approach		
Spatial representativeness in forest inventory, soil surveys, geological and geomorphological assessments		✔
Regular maintenance, cleaning and checking of measuring equipment	✔	
Suitability for snow precipitation	✔	
Constraints on lysimeter operation	✔	
Placement of loggers in caves		✔
Challenges with cellular dataloggers		✔
iii.) Opportunities for the proposed monitoring approach		
Enhanced protection for throughfall monitoring	✔	
Tailored sampling strategies for karst aquifers		✔
Technological progress	✔	
Refinement of drop counter sampling methods		✔
Development of spatial and temporal conceptual models of the KCZ vertical profile		✔
Scaling from plot-level to catchment or aquifer scale	✔	
Future research opportunities	✔	
iv.) Threats to proposed monitoring approach		
Danger from environmental influences	✔	
Vulnerability to equipment tampering	✔	
Insufficient rainfall during event-based sampling		✔
Accessibility and hydrological variability		✔
Stability of long-term funding	✔	

iii.) Opportunities for the proposed monitoring approach

- Enhanced protection for throughfall monitoring: the equipment can be outfitted with protective nets, mitigating the risk of rain gauge clogging and ensuring uninterrupted data collection.
- Tailored sampling strategies for karst aquifers: the sampling equipment, spatial layout of sampling plots, and sampling frequency can be customized to accommodate the unique characteristics of karst aquifers, optimizing data collection and analysis.
- Technological progress offers the opportunity to improve monitoring by using automated tools alongside traditional direct and indirect methods. For example, by integrating in-situ sensor networks with remote sensing, direct measurements from sensors can be correlated with data from e.g. phenological cameras, drones and satellite imagery. This integration can provide comprehensive insights into environmental dynamics, facilitate more accurate assessments as well as scenario predictions.
- Refinement of drop counter sampling methods: there is an opportunity to improve the design of sampling methods for drop counters, enhancing their accuracy and reliability in measuring water infiltration rates.
- Development of spatial and temporal conceptual models of the KCZ vertical profile: the integrated monitoring efforts present an opportunity to develop conceptual models that leverage collected data to fill information and knowledge gaps, provide uncertainty estimates, and make predictions. This approach enhances understanding of complex systems and improves decision-making processes.
- Scaling from plot-level to catchment or aquifer scale: while scaling up from plot-level studies to catchment or aquifer scales poses challenges due to spatial uncertainty. The process requires a large number of sampling plots to account for spatial differences, which is resource-intensive, time-consuming, and costly. There is an opportunity to address this through innovative methods such as remote sensing and artificial intelligence. These technologies can enable more efficient data collection and analysis, facilitating broader-scale assessments and insights.
- Future research opportunities focus on expanding the range of monitored parameters to enhance the understanding of ecohydrological processes. Key additions include monitoring of various parameters (e.g. radon and CO_2 concentrations), additional laboratory (e.g. stable isotopes, eDNA, bacteria, microplastics) or mapping analyses (e.g. land-use or vegetation cover changes). These additions will improve the accuracy of models, refine data interpretation, and address both ecological and environmental challenges within the karst system.

iv.) Threats to proposed monitoring approach

- Danger from environmental influences: Electronic measurement systems used outdoors, especially in forests or caves, are susceptible to damage from disturbance by wild animals or natural hazards. Precipitation events and lightning strikes can cause the devices to malfunction or fail, which can disrupt data acquisition and monitoring operations.
- Vulnerability to equipment tampering: there is a risk of equipment tampering or vandalism, leading to malfunctions.
- Insufficient rainfall during event-based sampling campaigns can make effective implementation difficult, resulting in unsaturated soil and inactive drips, which complicates sampling efforts.
- Accessibility and hydrological variability: Accessibility and hydrological fluctuations, especially in caves, pose a significant threat to data collection. Reaching monitoring sites in caves often requires extensive logistical planning and physical effort. In addition, loggers can be located deep underwater, making data collection and maintenance impossible. If the loggers are placed too high above the water level, they cannot record conditions during extremely low water periods.
- Stability of long-term funding: Securing stable, continuous funding for long-term research infrastructures remains a challenge. Sustainable financial support is crucial for maintaining monitoring activities over longer periods of time.

6. Conclusions and new perspectives

This study identifies key research gaps in karst ecohydrology monitoring, including the lack of large-scale, holistic studies that address the infiltration, recharge, and groundwater flow. Current research often focuses on non-karst environments or is restricted to plot-level studies, with inadequate consideration of water resource quality and quantity. Furthermore, existing monitoring networks suffer from a fragmented, non-interdisciplinary approach and technical challenges, limiting their ability to assess karst systems at a regional or catchment scale. To address these gaps, this study emphasizes the urgent need for an integrated, multi-scale monitoring approach and proposes a unified monitoring strategy that integrates multiple environmental domains and provides a comprehensive framework for understanding the spatial and temporal dynamics of karst systems.

This specific data collection strategy will provide valuable insights into the flow and transport mechanisms in karst critical zones. The identified strengths of the advanced monitoring network include comprehensive spatial and temporal coverage of the karst critical zone, interdisciplinary collaboration, improved precipitation monitoring, technological innovation concerning lysimeters and development of customized solutions adjusted to microscale conditions. Reliable data transmission in areas with stable signals is emphasized.

However, challenges remain, such as spatial representativeness in heterogeneous karst environments, elimination of monitoring malfunctions (e.g. proper usage and placement of logging devices in caves) and reliable equipment operation. Opportunities for improvement include better protection of monitoring devices, refinement of existing monitoring and sampling methods (such as suitability of gutters for snow monitoring, optimizing lysimeters), integration of *in situ* sensor networks with additional parameters and analyses, remote sensing, and scaling from the plot level to the catchment or aquifer scale. Threats to this approach are environmental pressures, equipment tampering, hydrometeorological variability and stability of long-term funding.

Nevertheless, the proposed comprehensive monitoring approach has proven critical to observing environmental processes and offers a unique contribution to the study of karst critical zones. This monitoring can serve to expand knowledge of geophysical processes at spatial and temporal scales, quantify control mechanisms, test hypotheses, and develop mathematical, numerical, and conceptual models. The inclusion of multidisciplinary research, the compilation and sharing of data sets support innovative collaborations between scientific and technological communities. Through careful selection of monitoring sites and parameters, researchers can better manage the complexity of karst ecohydrology and pave the way for more informed water resource management and conservation strategies.

CRediT authorship contribution statement

Nataša Ravbar: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Metka Petrič:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mitja Ferlan:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Uroš Novak:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Janez Kermavnar:** Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lado Kutnar:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aleksander Marinšek:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel Žlindra:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Blaž Kogovšek:** Visualization, Validation, Formal analysis, Data curation. **Erika Kozamernik:** Visualization, Validation, Formal analysis, Data curation. **Cyril Mayaud:** Validation, Methodology, Formal analysis, Data curation, Conceptualization. **David Štefanič:** Validation, Investigation, Formal analysis, Data curation. **Sara Skok:** Methodology, Conceptualization. **Janez Mulec:** Methodology, Conceptualization. **Stanka Šebela:** Methodology, Conceptualization. **Urša Vilhar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The study was carried out within the framework of the eLTER Preparatory Phase Project (eLTER PPP), eLTER Advanced Community Project (eLTER PLUS) and »Development of research infrastructure for the international competitiveness of the Slovenian RRI space – RI-SI-LifeWatch«, financed by the Republic of Slovenia, Ministry of Education, Science and Sport and the European Union from the European Regional Development Fund. We thank the Slovenian Research Agency for financial support within the projects: Infiltration processes in forested karst aquifers under changing environment (No. J2-1743), Ecohydrological study of spatio-temporal dynamics in karst critical zones under different climate conditions (No. NK-0002), Evaluate the impact of climate change on the groundwater reserves and ecology of a karst aquifer flooding intermittently: the Upper Pivka Valley (No. J1-60004), the Research Programmes: "Karst Research" (No. P6-0119) and "Forest biology, ecology and technology" (No. P4–0107).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2026.135027.

Data availability

Data will be made available on request.

References

Ashley, G. M. (2001). Where are we headed? "Soft" rock research into the new millennium. National Research Council, Basic Research Opportunities in Earth Science, Washington.

Bakalowicz, M., 2005. Karst groundwater: a challenge for new resources. Hydrgeol. J. 13, 148–160. https://doi.org/10.1007/s10040-004-0402-9.

Baker, A., Berthelin, R., Cuthbert, M.O., Treble, P.C., Hartmann, A., the KSS Cave Studies Team, 2020. Rainfall recharge thresholds in a subtropical climate determined using a regional cave drip water monitoring network. J. Hydrol. 587, 125001. https://doi.org/10.1016/j.jhydrol.2020.125001.

Baker, A., Scheller, M., Oriani, F., Mariethoz, G., Hartmann, A., Wang, Z., Cuthbert, M. O., 2021. Quantifying temporal variability and spatial heterogeneity in rainfall recharge thresholds in a montane karst environment. J. Hydrol. 594, 125965. https://doi.org/10.1016/j.jhydrol.2021.125965.

Baker, A., Shanafield, M., Timms, W., Andersen, M.S., Priestley, S., Melo Zurita, M., 2024. An underground drip water monitoring network to characterize rainfall recharge of groundwater at different geologies, environments, and climates across Australia. Geosci. Instrum. Method. Data Syst. 13, 117–129. https://doi.org/10.5194/gi-13-117-2024.

Baker, S.C., Spies, T.A., Wardlaw, T.J., Balmer, J., Franklin, J.F., Jordan, G.J., 2013. The harvested side of edges: effect of retained forests on the re-establishment of biodiversity in adjacent harvested areas. For. Ecol. Manage. 302, 107–121. https://doi.org/10.1016/j.foreco.2013.03.024.

Bechtold, W.A., Patterson, P.L., Eds. (2005). The enhanced forest inventory and analysis program - national sampling design and estimation procedures., USDA Forest Service, Southern Research Station, Asheville, N.C., USA, pp. 90.

Bonacci, O., Pipan, T., Culver, D.C., 2009. A framework for karst ecohydrology. Environ. Geol. 56 (5), 891–900. https://doi.org/10.1007/s00254-008-1189-0.

Bottrell, S.H., Atkinson, T.C., 1992. Tracer study of flow and storage in the unsaturated zone of a karstic limestone aquifer. In: Hötzl, H., Werner, A. (Eds.), Tracer Hydrology. Balkema, Rotterdam, pp. 207–211.

Braun-Blanquet, J., 1964. Pflanzensoziologie: Grundzüge der Vegetationskunde, 3rd ed. Springer-Verlag, Berlin.

Breg Valjavec, M., Čarni, A., Žlindra, D., Zorn, M., Marinšek, A., 2022. Soil organic carbon stock capacity in karst dolines under different land uses. Catena 218, 106548. https://doi.org/10.1016/j.catena.2022.106548.

Cantón, Y., Villagarcía, L., José Moro, M., Serrano-Ortíz, P., Were, A., Javier Alcalá, F., Kowalski, A.S., Solé-Benet, A., Lázaro, R., Domingo, F., 2010. Temporal dynamics of soil water balance components in a karst range in southeastern Spain: estimation of potential recharge. Hydrol. Sci. J. 55, 737–753. https://doi.org/10.1080/02626667.2010.490530.

Cantonati, M., Stevens, L.E., Segadelli, S., Springer, A.E., Goldscheider, N., Celico, F., Filippini, M., Ogata, K., Gargini, A., 2020. Ecohydrogeology: the interdisciplinary convergence needed to improve the study and stewardship of springs and other groundwater-dependent habitats, biota, and ecosystems. Ecol. Ind. 110, 105803. https://doi.org/10.1016/j.ecolind.2019.105803.

Canullo, R., Starlinger, F., Granke, O., Fischer, R., Aamlid, D., Dupouey, J.L. (2020). Part VII.1: Assessment of Ground Vegetation. Version 2020-1. In: UNECE ICP Forests Programme Coordinating Centre (ed.): Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. Thünen Institute of Forest Ecosystems, Eberswalde, 14 p. + Annex [http://www.icpforests.org/manual.htm].

Cao, L., Cheng, Q., Wang, S., Xu, S., He, Q., Li, Y., Peng, T., Wang, S., 2025. Hydrological and geochemical responses to agricultural activities in a karst catchment: insights from spatiotemporal dynamics and source apportionment. Water 17 (22), 3264. https://doi.org/10.3390/w17223264.

Čar, J., 2018. geostructural mapping of karstified limestones. Geologija 61 (2), 133–162. https://doi.org/10.5474/geologija.2018.010.

Čar, J., Gospodarič, R., 1984. About geology of karst among Postojna, Planina and Cerknica. Acta Carsologica 12, 91–106.
Carrière, S.D., Chalikakis, K., Danquigny, C., Davi, H., Mazzilli, N., Ollivier, C., Emblanch, C., 2016. The role of porous matrix in water flow regulation within a karst unsaturated zone: an integrated hydrogeophysical approach. Hydrgeol. J. 24, 1905–1918. https://doi.org/10.1007/s10040-016-1425-8.
Carrière, S.D., Martin-StPaul, N.K., Cakpo, C.B., Patris, N., Gillon, M., Chalikakis, K., Davi, H., 2020. The role of deep vadose zone water in tree transpiration during drought periods in karst settings–Insights from isotopic tracing and leaf water potential. Sci. Total Environ. 699, 134332. https://doi.org/10.1016/j.scitotenv.2019.134332.
Chorover, J., Kretzschmar, R., Garcia-Pichel, F., Sparks, D.L., 2007. Soil biogeochemical processes within the critical zone. Elements 3 (5), 321–326. https://doi.org/10.2113/gselements.3.5.321.
Cinkus, G., Wunsch, A., Mazzilli, N., Liesch, T., Chen, Z., Ravbar, N., Jourde, H., 2022. Comparison of artificial neural networks and reservoir models for simulating karst spring discharge on five test sites in the Alpine and Mediterranean regions. Hydrol. Earth Syst. Sci. Discuss. 2022, 1–41. https://doi.org/10.5194/hess-27-1961-2023.
Clarke, N., Žlindra, D., Ulrich, E., Mosello, R., Derome, J., Derome, K., König, N., Lövblad, G., Geppert, F., Draaijers, G.P.J., Hansen, K., Thimonier, A., Waldner, P., Verstraeten, A. (2022). Part XIV: Sampling and Analysis of Deposition. Version 2022-1. In: Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests, eds.), Part XIV, United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution, ICP Forests Programme Co-ordinating Centre, Thünen Institute of Forest Ecosystems, Eberswalde, Germany, pp. 34. https://efaidnbmnnnibpcajpcglclefindmkaj/https://pureportal.inbo.be/files/82307340/ICP_Manual_2020_part14_Depo_version_2020_1.pdf.
Condon, L.E., Kollet, S., Bierkens, M.F.P., Fogg, G.E., Maxwell, R.M., Hill, M.C., et al., 2021. Global groundwater modeling and monitoring: Opportunities and challenges. Water Resour. Res. 57, e2020WR029500. https://doi.org/10.1029/2020WR029500.
Cools, N., De Vos, B. (2020). Part X: Sampling and Analysis of Soil. Version 2020-1. In: UNECEICP Forests Programme Co-ordinating Centre (ed.): Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. Thünen Institute of Forest Ecosystems, Eberswalde, Germany, 29 p + Annex [http://www.icp-forests.org/manual.htm].
Covington, M.D., Martin, J.B., Toran, L.E., Macalady, J.L., Sekhon, N., Sullivan, P.L., García Jr, Á.A., Heffernan, J.B., Graham, W.D., 2023. Carbonates in the critical zone. Earth's Future 11 (1), e2022EF002765. https://doi.org/10.1029/2022EF002765.
Ćuk Đurović, M., Petrič, M., Jemcov, I., Mulec, J., Grudnik, Z.M., Mayaud, C., Blatnik, M., Kogovšek, B., Ravbar, N., 2022. Multivariate statistical analysis of hydrochemical and microbiological natural tracers as a tool for understanding karst hydrodynamics (the Unica Springs, SW Slovenia). Water Resour. Res. 58 (11), e2021WR031831. https://doi.org/10.1029/2021WR031831.
Dasgupta, S., Mohanty, B.P., Köhne, J.M., 2006. Impacts of juniper vegetation and karst geology on subsurface flow processes in the Edwards Plateau, Texas. Vadose Zone J. 5, 1076–1085. https://doi.org/10.2136/vzj2005.0073.
Davi, H., Dufrêne, E., Francois, C., Le Maire, G., Loustau, D., Bosc, A., Rambal, S., Granier, A., Moors, E., 2006. Sensitivity of water and carbon fluxes to climate changes from 1960 to 2100 in European forest ecosystems. Agric. For. Meteorol. 141 (1), 35–56. https://doi.org/10.1016/j.agrformet.2006.09.003.
De Oliveira, R.A., Ramos, M.M., De Aquino, L.A., 2015. Chapter 8 - Irrigation Management. In: Santos, F., Borém, A., Caldas, C. (Eds.), Sugarcane. Academic Press, San Diego, pp. 161–183.
Dobbertin, M., Neumann, M., Levanič, T., Sanders, T.G.M., Skudnik, M., Krüger, I. (2020). Part V: Tree Growth Level II. Version 2020-1. In: Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests, eds.), United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution, ICP Forests Programme Co-ordinating Centre, Thünen Institute of Forest Ecosystems, Eberswalde, Germany, pp. 19.
Faimon, J., Bodláková, R., Pracný, P., Hebelka, J., 2016. Transfer of climatic variables by dripwater: a case study from Kateřinská Cave (Moravian Karst). Environ. Earth Sci. 75, 1151. https://doi.org/10.1007/s12665-016-5982-x.
Federer, C.A., Vorosmarthy, C., Fekete, B., 2003. Sensitivity of annual evaporation to soil and root properties in two models of contrasting complexity. J. Hydrometeorol. 4, 1276–1290. https://doi.org/10.1175/1525-7541(2003)004<1276:SOAETS>2.0.CO;2.
Ferlan, M., Eler, K., Simončič, P., Batič, F., Vodnik, D., 2016. Carbon and water flux patterns of a drought-prone mid-succession ecosystem developed on abandoned karst grassland. Agr Ecosyst Environ 220, 152–163. https://doi.org/10.1016/j.agee.2016.01.020.
Fernández-Ortega, J., Barberá, J.A., Andreo, B., 2024. Real-time karst groundwater monitoring and bacterial analysis as early warning strategies for drinking water supply contamination. Sci. Total Environ. 912, 169539. https://doi.org/10.1016/j.scitotenv.2023.169539.
Ferretti, M., Fischer, R. Eds. (2013). Forest Monitoring. Terrestrial Methods in Europe with Outlook to North America and Asia. Developments in Environmental Science 12, Elsevier, Amsterdam, pp. 507.
Ford, D., Williams, P., 2007. Karst Hydrogeology and Geomorphology. Wiley, Chichester, UK.
Frank, S., Goeppert, N., Goldscheider, N., 2018. Fluorescence-based multi-parameter approach to characterize dynamics of organic carbon, faecal bacteria and particles at alpine karst springs. Sci. Total Environ. 615, 1446–1459. https://doi.org/10.1016/j.scitotenv.2017.09.095.
Fu, T., Chen, H., Fu, Z., Wang, K., 2016. Surface soil water content and its controlling factors in a small karst catchment. Environ. Earth Sci. 75, 1406. https://doi.org/10.1007/s12665-016-6222-0.
Fu, Z.Y., Chen, H.S., Zhang, W., Xu, Q.X., Wang, S., Wang, K.L., 2015. Subsurface flow in a soil-mantled subtropical dolomite karst slope: a field rainfall simulation study. Geomorphology 250, 1–14. https://doi.org/10.1016/j.geomorph.2015.08.012.
Gabrovšek, F., Kogovšek, J., Kovačič, G., Petrič, M., Ravbar, N., Turk, J., 2010. Recent results of tracer tests in the catchment of the Unica River (SW Slovenia). Acta Carsologica 39 (1), 27–37. https://doi.org/10.3986/ac.v39i1.110.
Geekiyanage, N., Goodale, U.M., Cao, K., Kitajima, K., 2019. Plant ecology of tropical and subtropical karst ecosystems. Biotropica 51 (5), 626–640. https://doi.org/10.1111/btp.12696.
Goldscheider N, Drew D (eds) (2007) Methods in karst hydrogeology. International Contribution to Hydrogeology, IAH, vol 26. Taylor and Francis/Balkema, London, pp. 264.
Goldscheider, N., Chen, Z., Auler, A.S., Bakalowicz, M., Broda, S., Drew, D., Veni, G., 2020. Global distribution of carbonate rocks and karst water resources. Hydrgeol. J. 28, 1661–1677. https://doi.org/10.1007/s10040-020-02139-5.
Grčman, H., Vidic, N. J., Zupan, M., Lobnik, F., Jones, A., Montanarella, L. (2015). Soils of Slovenia with soil map 1:250.000. European Commission JRC In-titute for Environment and Sustainability, pp. 187, Luxemburg.
Gustavsson, M., Kolstrup, E., Seijmonsbergen, A.C., 2006. A new symbol-and-GIS based detailed geomorphological mapping system: Renewal of a scientific discipline for understanding landscape development. Geomorphology 77 (1–2), 90–111. https://doi.org/10.1016/j.geomorph.2006.01.026.
Hammel, K., Kennel, M., 2001. Charakterisierung und Analyse der Wasserverfuegbarkeit und des Wasserhaushalts von Waldstandorten in Bayern mit dem Simulationsmodell BROOK90. Forstliche Forschungsberichte München 185, 135.
Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., Weiler, M., 2014. Karst water resources in a changing world: Review of hydrological modeling approaches. Rev. Geophys. 52 (3), 218–242. https://doi.org/10.1002/2013RG000443.
Häuselmann, P., 2002. UIS Cave symbols: the definitive list. Acta Carsologica 31 (3). https://doi.org/10.3986/ac.v31i3.386.
Heilman, J., Litvak, M.E., Mcinnes, K.J., Kjelgaard, J.F., Schwinning, S., 2012. Water-storage capacity controls energy partitioning and water use in karst ecosystems on the Edwards Plateau, Texas. Ecohydrology 7, 127–138. https://doi.org/10.1002/eco.1327.
Heimel, S.M., Tobin, B.W., 2022. Geospatial applications of cave resource data to better understand epikarst and unsaturated zone groundwater flow path development. Geosciences 12 (2), 47. https://doi.org/10.3390/geosciences12020047.
ICOS (2022). ICOS HANDBOOK 2022. Integrated Carbon Observation System Research Infrastructure (ICOS) Handbook 2022. ICOS ERIC, Helsinki. https://efaidnbmnnnibpcajpcglclefindmkaj/https://www.icos-cp.eu/sites/default/files/2022-03/ICOS_handbook_2022_WEB.pdf.
ICP Integrated monitoring (2022). Manual for Integrated Monitoring. Edition 7. United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution, International Cooperative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems, The Swedish University of Agricultural Sciences, pp. 213. https://efaidnbmnnnibpcajpcglclefindmkaj/https://www.slu.se/globalassets/ew/org/centrb/im/im_manual_edition_7.pdf.
ICP Waters, 2010. ICP Waters Programme Manual. United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution, International Cooperative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems. ICP Waters Programme Center. Norwegian Institute for Water Research, Oslo, p. 213.
INSPIRE Infrastructure for Spatial Information in Europe (2024). Data Specification on Geology – Technical Guidelines. INSPIRE Maintenance and Implementation Group. https://knowledge-base.inspire.ec.europa.eu/publications/inspire-data-specification-geology-technical-guidelines_en.
Ismail, M.F., Bogacki, W., Disse, M., Schäfer, M., Kirschbauer, L., 2023. Estimating degree-day factors of snow based on energy flux components. Cryosphere 17 (1), 211–231. https://doi.org/10.5194/tc-17-211-2023.
ISO 11277, 2020. Soil quality — Determination of particle size distribution in mineral soil material — Method by sieving and sedimentation. ISO, Geneva, Switzerland.
ISO 5667–1, 2023. Water quality — Sampling — Part 1: Guidance on the design of sampling programs and sampling techniques. ISO, Geneva, Switzerland.
Jiang, G., Guo, F., Liu, F., Li, Z., Milanović, S., 2025. Hydrogeological responses of karst compartments to meteorological drought in subtropical monsoon regions. J. Hydrol. 655, 132940. https://doi.org/10.1016/j.jhydrol.2025.132940.
Katzensteiner, K., 2003. Effects of harvesting on nutrient leaching in a Norway spruce (*Picea abies* Karst.) ecosystem on a Lithic Leptosol in the Northern Limestone Alps. Plant and Soil 250, 59–73. https://doi.org/10.1023/A:1022821913932.
Klaas, D.K., Imteaz, M.A., Sudiayem, I., Klaas, E.M., Klaas, E.C., 2020. Assessing climate changes impacts on tropical karst catchment: Implications on groundwater resource sustainability and management strategies. J. Hydrol. 582, 124426. https://doi.org/10.1016/j.jhydrol.2019.124426.
Kobal, M., Bertoncelj, I., Pirotti, F., Dakskobler, I., Kutnar, L., 2015. Using Lidar data to analyse sinkhole characteristics relevant for understory vegetation under forest cover – case study of a high karst area in the Dinaric Mountains. PLoS One 10, e0122070. https://doi.org/10.1371/journal.pone.0122070.
Kobal, M., Urbančič, M., Kralj, T., Simončič, P. (2007). Navodila za vzorčenje tal na 4 x 4 kilometrski mreži velikoprostorskega popisa poškodovanosti gozdov in gozdnih ekosistemov v letu 2007. Interno gradivo. 21 str.
Koch, E., Bruns, E., Chmielewsk, F.M., Defila, C., Lipa, W., Menzel, A. (2009). Guidelines for Commission for Plant Phenological Observations. WMO Technical Climatology,

Open Program Area Group on Monitoring and Analysis of Climate Variability and Change (OPAG2), Geneva, pp. 16.
Kogovšek, J. (2010). Characteristics of percolation through the karst vadose zone (Vol. 10). Založba ZRC.
Kovačič, G., Petrič, M., Ravbar, N., 2020. Evaluation and quantification of the effects of climate and vegetation cover change on karst water sources: Case studies of two springs in South-Western Slovenia. Water 12 (11), 3087. https://doi.org/10.3390/w12113087.
Krečmer, V. (1967). Das Mikroklima der Kieferlochkahlschlaege. IV Teil: Vertikale Niederschlaege, Luftfeuchtigkeit. Wetter und Leben, 19, 9-10: 203-214.
Kutnar, L., Kermavnar, J., Pintar, A.M., 2021. Climate change and disturbances will shape future temperate forests in the transition zone between Central and SE Europe. Ann. For. Res. https://doi.org/10.15287/afr.2021.2111.
LAI-2200 (2012). Plant canopy analyzer: instruction manual. LI-COR, Inc. , Lincoln, pp. 222.
Lee, R.M., Shoshitaishvili, B., Buck, R.L., Bekker, J., Abbott, B.W., 2023. The meanings of the critical Zone. Anthropocene 100377. https://doi.org/10.1016/j.ancene.2023.100377.
Lenk, A., Richter, R., Kretz, L., Wirth, C., 2024. Effects of canopy gaps on microclimate, soil biological activity and their relationship in a European mixed floodplain forest. Sci. Total Environ. 941, 173572. https://doi.org/10.1016/j.scitotenv.2024.173572.
Li, Y., Wang, S., Peng, T., Zhao, G., Dai, B., 2023. Hydrological characteristics and available water storage of typical karst soil in SW China under different soil–rock structures. Geoderma 438, 116633. https://doi.org/10.1016/j.geoderma.2023.116633.
Liu, F., Jiang, G., Wang, J., Guo, F., 2021. The recharge process and influencing meteorological parameters indicated by cave pool hydrology in the Bare Karst Mountainous Area. Sustainability 13, 1766. https://doi.org/10.3390/su13041766.
Long, D.T., Pearson, A.L., Voice, T.C., Polanco-Rodríguez, A.G., Sanchez-Rodríguez, E.C., Xagoraraki, I., Rzotkiewicz, A.T., 2018. Influence of rainy season and land use on drinking water quality in a karst landscape, State of Yucatán, Mexico. Appl. Geochem. 98, 265–277. https://doi.org/10.1016/j.apgeochem.2018.09.020.
Mahler, B.J., Jiang, Y., Pu, J., Martin, J.B., 2021. Advances in hydrology and the water environment in the karst critical zone under the impacts of climate change and anthropogenic activities. J. Hydrol. 595, 125982. https://doi.org/10.1016/j.jhydrol.2021.125982.
Mollenhauer, H., Kasner, M., Haase, P., Peterseil, J., Wohner, C., Frenzel, M., Zacharias, S., 2018. Long-term environmental monitoring infrastructures in Europe: observations, measurements, scales, and socio-ecological representativeness. Sci. Total Environ. 624, 968–978. https://doi.org/10.1016/j.scitotenv.2017.12.095.
Moore, G., Mcguire, K., Troch, P., Barron-Gafford, G. (2015). Chapter 8 - Ecohydrology and the Critical Zone: Processes and Patterns Across Scales. In: Developments in Earth Surface Processes (J.R. Giardino and C. Houser, eds.), 19, Elsevier, pp. 239-266. https://www.sciencedirect.com/science/article/abs/pii/B9780444633699000082?via%3Dihub.
Morrissey, P., Nolan, P., McCormack, T., Johnston, P., Naughton, O., Bhatnagar, S., Gill, L., 2021. Impacts of climate change on groundwater flooding and ecohydrology in lowland karst. Hydrol. Earth Syst. Sci. 25 (4), 1923–1941. https://doi.org/10.5194/hess-25-1923-2021.
Mueller, M.H., Weingartner, R., Alewell, C., 2013. Importance of vegetation, topography and flow paths for water transit times of base flow in alpine headwater catchments. Hydrol. Earth Syst. Sci. 17, 1661–1679. https://doi.org/10.5194/hess-17-1661-2013.
Nagel, T.A., Firm, D., Rozenbergar, D., Kobal, M., 2016. Patterns and drivers of ice storm damage in temperate forests of Central Europe. Eur. J. For. Res. 135, 519–530. https://doi.org/10.1007/s10342-016-0950-2.
Nava-Fernandez, C., Hartland, A., Gázquez, F., Kwiecien, O., Marwan, N., Fox, B., Hellstrom, J., Pearson, A., Ward, B., French, A., Hodell, D.A., Immenhauser, A., Breitenbach, S.F.M., 2020. Pacific climate reflected in Waipuna Cave drip water hydrochemistry. Hydrol. Earth Syst. Sci. 24, 3361–3380. https://doi.org/10.5194/hess-24-3361-2020.
Nieminen, T.M., De Vos, B., Cools, N., König, N., Fischer, R., Iost, S., Meesenburg, H., Nicolas, M., O'dea, P., Cecchini, G., Ferretti, M., De La Cruz, A., Derome, K., Lindroos, A.J., Graf Pannatier, E. (2016). UNECE ICP Forests Programme Co-ordinating Centre of ICP Forests, Part XI: Soil Solution Collection and Analysis. In: Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests, eds.), Version 2016-2, UNECE ICP Forests Programme Co-ordinating Centre of ICP Forests, Federal Research Centre for Forestry and Forest Products (BFH). Forest Soil Co-ordinating Centre (FSCC), Ghent University, Thünen Institute of Forest Ecosystems, Eberswalde, Germany, pp. 20. http://www.icp-forests.org/manual.htm.
Niu, X., Fan, J., Luo, R., Fu, W., Yuan, H., Du, M., 2021. Continuous estimation of leaf area index and the woody-to-total area ratio of two deciduous shrub canopies using fisheye webcams in a semiarid loessial region of China. Ecol. Ind. 125, 107549. https://doi.org/10.1016/j.ecolind.2021.107549.
Ohnemus, T., Zacharias, S., Dirnböck, T., Bäck, J., Brack, W., Forsius, M., Mallast, U., Nikolaidis, N.P., Peterseil, J., Piscart, C., Pando, F., Terán, C.P., Mirtl, M., 2024. The eLTER research infrastructure: current design and coverage of environmental and socio-ecological gradients. Environ. Sustainability Indic. 23. https://doi.org/10.1016/j.indic.2024.100456.
OJ EC (2000). Water Framework Directive (WFD). Official Journal 2000/60/EC.
Olarinoye, et al., 2020. Global karst springs hydrograph dataset for research and management of the world's fastest-fowing groundwater. Sci. Data 7, 59. https://doi.org/10.1038/s41597-019-0346-5.
Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 11, 1633–1644. https://doi.org/10.5194/hess-11-1633-2007.
Piao, S., Friedlingstein, P., Ciais, P., Viovy, N., Demarty, J., 2007. Growing season extension and its impact on terrestrial carbon cycle in the Northern Hemisphere over the past 2 decades. Global Biogeochem. Cycles 21, 3. https://doi.org/10.1029/2006GB002888.
Pickett, S.T.A., 1989. Space-for-Time Substitution as an Alternative to Long-Term Studies. In: Likens, G.E. (Ed.), Long-Term Studies in Ecology: Approaches and Alternatives. Springer, New York, New York, NY, pp. 110–135.
Pipan, T., Aljančič, M., 2024. 20 years of LTER Slovenia. Acta Carsologica 53 (2–3), 203–209. https://doi.org/10.3986/ac.v53i2-3.13535.
Pipan, T., Petrič, M., Šebela, S., Culver, D.C., 2018. Analyzing climate change and surface-subsurface interactions using the Postojna Planina Cave System (Slovenia) as a model system. Reg. Environ. Chang. 19, 379–389. https://doi.org/10.1007/s10113-018-1349-z.
Pörtner, H.O., Roberts, D.C., Adams, H., Adler, C., Aldunce, P., Ali, E., ... Ibrahim, Z.Z. (2022). Climate change 2022: impacts, adaptation and vulnerability. IPCC.
Poulain, A., Watlet, A., Kaufmann, O., Van Camp, M., Jourde, H., Mazzilli, N., Rochez, G., Deleu, R., Quinif, Y., Hallet, V., 2018. Assessment of groundwater recharge processes through karst vadose zone by cave percolation monitoring. Hydrol. Process. 32, 2069–2083. https://doi.org/10.1002/hyp.13138.
Quinlan, F.J. (1989). Ground-Water Monitoring In Karst Terranes Recommended Protocols and Implicit Assumptions, 1989, Environmental Monitoring System Laboratory, Las Vegas, NV, USA (1989), p. 79.
Raspe, S., Fleck, S., Beuker, E., Preuhsler, T., Bastrup-Birk, A. (2020). Part IX: Meteorological Measurements. Version 2020-1. United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution, ICP Forests Programme Co-ordinating Centre, Thünen Institute of Forest Ecosystems, Eberswalde, Germany, pp. 18.
Ravbar, N., Šebela, S., 2015. The effectiveness of protection policies and legislative framework with special regard to karst landscapes: Insights from Slovenia. Environ. Sci. Policy 51, 106–116. https://doi.org/10.1016/j.envsci.2015.02.013.
Ravbar, N., Mulec, J., Mayaud, C., Blatnik, M., Kogovšek, B., Petrič, M., 2023. A comprehensive early warning system for karst water sources contamination risk, case study of the Unica springs, SW Slovenia. Sci. Total Environ. 885, 163958. https://doi.org/10.1016/j.scitotenv.2023.163958.
Ravbar, N., Barborič, B., Kovačič, G., 2024. Multi-decadal changes in vegetation and land use inferred from different data sources: Two case studies at the regional scale in the Slovenian karst. Land Degrad. Dev. 35 (15), 4696–4710. https://doi.org/10.1002/ldr.5250.
Remane, J., Bassett, M.G., Cowie, J.W., Gohrbandt, K.H., Lane, H.R., Michelsen, O., Naiwen, W., 1996. Revised guidelines for the establishment of global chronostratigraphic standards by the International Commission on Stratigraphy (ICS). Episodes J. Int. Geosci. 19 (3), 77–81.
Sarrazin, F., Hartmann, A., Pianosi, F., Rosolem, R., Wagener, T., 2018. V2Karst V1. 1: a parsimonious large-scale integrated vegetation–recharge model to simulate the impact of climate and land cover change in karst regions. Geosci. Model Dev. 11 (12), 4933–4964. https://doi.org/10.5194/gmd-11-4933-2018.
Schwärzel, K., Seidling, W., Hansen, K., Strich, S., Lorenz, M. 2022. Part I: Objectives, Strategy and Implementation of ICP Forests. Version 2022-2. In: Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests, eds.), United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution, ICP Forests Programme Coordinating Centre, Thünen Institute of Forest Ecosystems, Eberswalde, Germany, pp. 12.
Šebela, S., 2021. Natural and Anthropogenic Impacts on Cave Climates. Postojna and Predjama Show Caves (Slovenia). Elsevier.
Šebela, S., Novak, U., 2023. Geological structure of karst stratigraphical windows at škocjan Caves. Slovenia. SN Appl. Sci. 5, 104. https://doi.org/10.1007/s42452-023-05330-x.
Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Reyer, C.P., 2017. Forest disturbances under climate change. Nat. Clim. Chang. 7 (6), 395–402. https://doi.org/10.1038/nclimate3303.
Siegel, L., Goldscheider, N., Petitta, M., Xanke, J., Andreo, B., Bakalowicz, M., Stevanović, Z., 2023. Distribution, threats and protection of selected karst groundwater-dependent ecosystems in the Mediterranean region. Hydrgeol. J. 31 (8), 2231–2249. https://doi.org/10.1007/s10040-023-02711-9.
Stevanović, Z., 2019. Karst waters in potable water supply: a global scale overview. Environ. Earth Sci. 78 (23), 662. https://doi.org/10.1007/s12665-019-8670-9.
Stevanović, Z., Gunn, J., Goldscheider, N., Ravbar, N., 2024. Karst: environment and management of aquifers. The Groundwater Project. https://doi.org/10.62592/AWCU2984.
Stevanović, Z., Stevanović, A.M., 2021. Monitoring as the key factor for sustainable use and protection of groundwater in Karst environments—an overview. Sustainability 13 (10), 5468. https://doi.org/10.3390/su13105468.
Szczygieł, J., Sobczyk, A., Maciejewski, M., Fernandez, O., 2022. Variscan vs. Alpine structural controls: Karstic proto-conduit development within Palaeozoic marble post-conditioned by Alpine faulting (the Niedźwiedzia Cave, NE Bohemian Massif). Geomorphology 415 (108423). https://doi.org/10.1016/j.geomorph.2022.108423.
Taylor C.J., Greene E.A. (2008). Hydrogeologic characterization and methods used in the investigation of karst hydrology. Field techniques for estimating water fluxes between surface water and ground water, 71–114.
Polk, T.B.W., Arpin, S.M., Shelley, A., Taylor, C., 2021. A conceptual model of epikarst processes across sites, seasons, and storm events. J. Hydrol. 596, 125692. https://doi.org/10.1016/j.jhydrol.2020.125692.

Tramblay, Y., Koutroulis, A., Samaniego, L., Vicente-Serrano, S.M., Volaire, F., Boone, A., Polcher, J., 2020. Challenges for drought assessment in the Mediterranean region under future climate scenarios. Earth Sci. Rev. 210, 103348. https://doi.org/10.1016/j.earscirev.2020.103348.

Ungar, E.D., Rotenberg, E., Raz-Yaseef, N., Cohen, S., Yakir, D., Schiller, G., 2013. Transpiration and annual water balance of Aleppo pine in a semiarid region: Implications for forest management. For. Ecol. Manage. 298, 39–51. https://doi.org/10.1016/j.foreco.2013.03.003.

USGS, 2006. National field manual for the collection of water-quality data (Techniques of Water-Resources Investigations, Book 9). U.S. Geological Survey, Reston, VA, 10.3133/twri09.

Vilhar, U., 2010. Padavinski režim v vrzelih in sestojih dinarskega jelovo-bukovega gozda. Precipitation regime in gaps and mature stands of Dinaric silver fir-beech forests. Zbornik Gozdarstva in Lesarstva / Acta Silva et Ligni 91, 3–10.

Vilhar, U., Kermavnar, J., Kozamernik, E., Petrič, M., Ravbar, N., 2022. The effects of large-scale forest disturbances on hydrology–an overview with special emphasis on karst aquifer systems. Earth Sci. Rev. 104243. https://doi.org/10.1016/j.earscirev.2022.104243.

Vilhar, U., Simončič, P., 2012. Water status and drought stress after gap formation in managed and semi-natural silver fir - beech forests. Eur. J. For. Res. 131 (5), 1381–1397. https://doi.org/10.1007/s10342-012-0605-x.

Vilhar, U., Starr, M., Katzensteiner, K., Simončič, P., Kajfež-Bogataj, L., Diaci, J., 2010. Modelling drainage fluxes in managed and natural forests in the Dinaric karst: a model comparison study. Eur. J. For. Res. 129, 729–740. https://doi.org/10.1007/s10342-010-0379-y.

Vilhar, U., Starr, M., Urbančič, M., Smolej, I., Simončič, P., 2005. Gap evapotranspiration and drainage fluxes in a managed and a virgin dinaric silver fir–beech forest in Slovenia: a modelling study. Eur. J. For. Res. 124, 165–175. https://doi.org/10.1007/s10342-005-0067-5.

Von Arx, G., Graf Pannatier, E., Thimonier, A., Rebetez, M., 2013. Microclimate in forests with varying leaf area index and soil moisture: potential implications for seedling establishment in a changing climate. J. Ecol. 101 (5), 1201–1213. https://doi.org/10.1111/1365-2745.12121.

Watlet, A., Kaufmann, O., Triantafyllou, A., Poulain, A., Chambers, J.E., Meldrum, P.I., Van Camp, M., 2018. Imaging groundwater infiltration dynamics in the karst vadose zone with long-term ERT monitoring. Hydrol. Earth Syst. Sci. 22 (2), 1563–1592. https://doi.org/10.5194/hess-22-1563-2018.

White, T., Brantley, S., Banwart, S., Chorover, J., Dietrich, W., Derry, L., ... & McDowell, B. (2015). The role of critical zone observatories in critical zone science. In Developments in earth surface processes (Vol. 19, pp. 15-78). Elsevier. Doi: 10.1016/B978-0-444-63369-9.00002-1.

Willimas, P.W., 2008. The role of the epikarst in karst and cave hydrogeology: a review. Int. J. Speleol. 37, 1–10. https://doi.org/10.5038/1827-806X.37.1.1.

WMO, 2008. Guide to hydrological practices: Volume I & II (WMO-No. 168). Geneva, Switzerland: World Meteorological Organization.

WMO, 2023. Guide to Instruments and Methods of Observation. Volume I - Measurement of Meteorological Variables, 2023 edition ed. World Meteorological Organization.

Wogan, G.O.U., Wang, I.J., 2018. The value of space-for-time substitution for studying fine-scale microevolutionary processes. Ecography 41, 1456–1468. https://doi.org/10.1111/ecog.03235.

Wunsch, A., Liesch, T., Cinkus, G., Ravbar, N., Chen, Z., Mazzilli, N., Jourde, H., Goldscheider, N., 2022. Karst spring discharge modeling based on deep learning using spatially distributed input data. Hydrol. Earth Syst. Sci. 26 (9), 2405–2430. https://doi.org/10.5194/hess-26-2405-2022.

Zhang, Z., Chen, X., Ghadouani, A., Shi, P., 2011. Modelling hydrological processes influenced by soil, rock and vegetation in a small karst basin of southwest China. Hydrol. Process. 25, 2456–2470. https://doi.org/10.1002/hyp.8022.

Žlindra, D., Eler, K., Clarke, N., Simončič, P., 2011. Towards harmonization of forest deposition collectors - case study of comparing collector designs. iForest - Biogeosc. For. 4, 218–225. https://doi.org/10.3832/ifor0586-004.