

The WoKaS-Iso database: workflow for a global compilation of Oxygen-18 and Deuterium records in karst springs and cave drip water for enhanced understanding of karst systems

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1 **The WoKaS-Iso Database: Workflow for a Global Compilation of Oxygen-18 and Deuterium**
2 **Records in Karst Springs and Cave Drip Water for Enhanced Understanding of Karst Systems**

3

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72 **Abstract**

73 For analysing karst hydrogeological systems, observations of karst springs and cave drips are considered indispensable. In
74 addition to hydrometric observations, knowing the oxygen and hydrogen stable isotope ratios has improved the understanding
75 of vadose zone and aquifer dynamics, likewise supporting system characterisation and modelling. However, limited
76 accessibility and high costs of the analysis of stable isotopes in karst aquifers have hindered progress in karst research and
77 impeded the accurate understanding of karst processes especially when it comes to comparative or large-scale studies. In this
78 study, we present our workflow to compile the WoKaS-Iso database, the first extensive collection of time series data for
79 Oxygen-18 and Deuterium isotopes in karst springs and cave drip water from diverse sources, encompassing publications,
80 theses, reports, online archives, and collaborative initiatives worldwide. The database incorporates data sourced from 236
81 springs and 74 caves, comprising in total 997 time series (379 time series for the springs and 618 time series for the cave drip
82 water). These datasets provide coverage across significant karst regions globally, spanning China, the USA, Europe, the Middle
83 East, and Australia. Within datasets, 79% for springs and 68% for cave drip water exhibit resolutions finer than monthly



84 intervals. In addition, by integrating isotopic records with ancillary environmental variables including spring discharge, cave
85 drip rate, precipitation, and rainwater isotopes, the database offers a more comprehensive perspective on hydrological
86 behaviours in karst aquifers, hence advancing hydrogeological characterisation and modelling. The WoKaS-Iso database not
87 only deepens the understanding of the complex systems but also promotes sustainable water resource management as well as
88 the potential to foster collaborative research. The database can be accessed at: <https://doi.org/10.25532/OPARA-909> (Zang,
89 2025).

90 **1 Introduction**

91 Carbonate rock areas, particularly those with highly karstified systems, serve as a critical source of potable water, catering
92 10%–25% of the global population (Ford and Williams, 2007; Stevanović, 2019) and up to 50% in some countries (European
93 Cooperation in Science and Technology, 1995). Beyond water supply, these aquifers encompass extensive cave networks that
94 preserve valuable paleoclimate records, reflecting key variability patterns of past environmental conditions (McDermott, 2004).
95 The karstification leads to inherent structural heterogeneity and strong nonlinearities of hydraulic properties (Frank et al., 2021;
96 Jourde et al., 2018; Labat et al., 2016) that drive subsurface water flow regimes and storage mechanisms including fast conduit
97 turbulent flow and slow matrix storage (Bakalowicz, 2005; Goldscheider and Drew, 2007) while challenging characterization
98 of karst aquifer structures, hydraulic dynamics, and contamination pathways. Consequently, a comprehensive understanding
99 of hydrogeological behaviours in karst systems is essential for sustainable water resource management and protection. This is
100 also a matter of urgency for certain European regions that appear to be sensitive to the effects of global warming (Giese et al.,
101 2025).

102

103 Stable isotopes of oxygen and hydrogen, being part of the water molecule itself, are ideal tracers for identifying water sources
104 (Hartmann et al., 2014) delineating subsurface flow paths, estimating transit times (Liu and Yamanaka, 2012; McDonnell et
105 al., 2010), and quantifying mixing processes (Rusjan et al., 2019). In karst hydrogeology, spring isotope signatures integrating
106 responses from both saturated and unsaturated zones often give additional information about complex recharge patterns that
107 are not captured by discharge data alone. Isotope data thus provide critical complementary information to resolve flow and
108 transport dynamics. Meanwhile, in speleological research, stable isotopes are central to understanding recharge processes
109 through the epikarst, providing a distinctive window into unsaturated zone and recharge processes (Hartmann and Baker, 2017).
110 Cave drips act as a medium to monitor flow path through epikarst that is directly linked to climate signals preserved in
111 speleothem formed from cave drips which can serve as archives for paleoclimate reconstruction (Bradley et al., 2010;
112 MacDermott et al., 2006). Long-term rainfall and drip water monitoring is crucial for distinguishing local or regional climatic
113 influences on cave system isotope variability (Pape et al., 2010). Moreover, stable isotopes provide critical information on
114 water transit times through karst systems, allowing the identification of fast conduit flow versus slow matrix storage
115 contributions. This capability is essential for understanding the temporal dynamics of recharge, flow pathways, and aquifer



116 vulnerability to contamination, as it directly links precipitation events to spring or cave drip responses. Incorporating isotope-
117 based transit time estimates into hydrological models enhances the characterization of flow heterogeneity and improves
118 predictions of contaminant transport and residence times within karst aquifers.

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120 More recently, isotope-based models have emerged to couple hydrological dynamics with stable isotopes (Birkel and Soulsby,
121 2015; Zhang et al., 2019). Andreo et al. (2004) applied $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in precipitation and groundwater to determine the water
122 origin and understand the aquifer dynamics in the Yunquera-Nieves karstic massif in Spain. Wang et al. (2022) coupled
123 hydrochemical and stable isotopic compositions to identify the groundwater hydrochemistry evolution in the Western Yellow
124 Sea Coast of China. Hartmann et al. (2012) utilized isotopic information ($\delta^{18}\text{O}$) to calibrate their recharge model. Hydrological
125 functions such as water storage, flux and water age distributions are effectively quantified by these isotope-coupled models,
126 providing essential indicators of understanding the behaviour of the karst aquifer (Mayer-Anhalt et al., 2022). Additionally,
127 coupling isotopic and hydrological data has proven valuable for facilitating the multi-objective calibration and validation
128 (Hartmann et al., 2013) enhancing the model evaluation, mitigating overparameterization and reducing the potential
129 uncertainties (Li et al., 2022; Zhang et al., 2019). On the other hand, recent cave-based research has used stable water isotopes
130 to advance the understanding of karst vadose zone hydrology. Priestley et al. (2023) combined $\delta^{18}\text{O}$ from speleothems and drip
131 waters with modelled soil moisture data to show how regional drying in southwestern Australia disrupted rainfall recharge to
132 shallow karst aquifers—an unprecedented shift over the past 800 years. Baker et al. (2019) analyzed $\delta^{18}\text{O}$ from 163 global drip
133 sites and found that in seasonal climates, drip water isotopes reflect recharge-weighted precipitation, refining the interpretation
134 of speleothem records. Treble et al. (2022) demonstrated that isotopic variability within caves is largely driven by differences
135 in flow path properties—fracture versus matrix flow—highlighting the importance of hydrological heterogeneity in shaping
136 $\delta^{18}\text{O}$ signals. Together, these studies underline the growing potential of isotope-hydrology approaches for resolving spatial and
137 temporal variability in karst recharge and for reconstructing past hydroclimatic conditions. All these applications highlight the
138 growing value of isotopic datasets for both process understanding and model development in karst systems.

139

140 Several global databases have been established to archive stable water isotope data, most notably the Global Network of
141 Isotopes in Precipitation (GNIP) and the Global Network of Isotopes in Rivers (GNIR) maintained by the International Atomic
142 Energy Agency (IAEA) and World Meteorological Organization (WMO). In addition, Staudinger et al. (2020) developed a
143 long-term $\delta^{18}\text{O}$ and $\delta^2\text{H}$ database for streamflow and precipitation for 23 catchments in Switzerland, and Li et al. (2025)
144 established the first global surface water stable isotope database from measured data, web-sourced records and referenced data.
145 While these databases provide essential insights into hydrological processes, they largely omit $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data from karst
146 springs and cave drip waters. $\delta^{18}\text{O}$ and $\delta^2\text{H}$ signatures in karst springs and cave drip waters as natural tracers have been proven
147 invaluable, offering insights into characterizing recharge patterns, validating and enhancing the accuracy of hydrological
148 models and calibrating the reconstruction of paleoclimate through speleothem records (Tremaine et al., 2011). Despite the



149 significance, the broader use of isotopic applications remained constrained by the high cost of stable isotope analysis and
150 limited accessibility to the existing datasets for large-scale modelling and comparative studies across karst regions.

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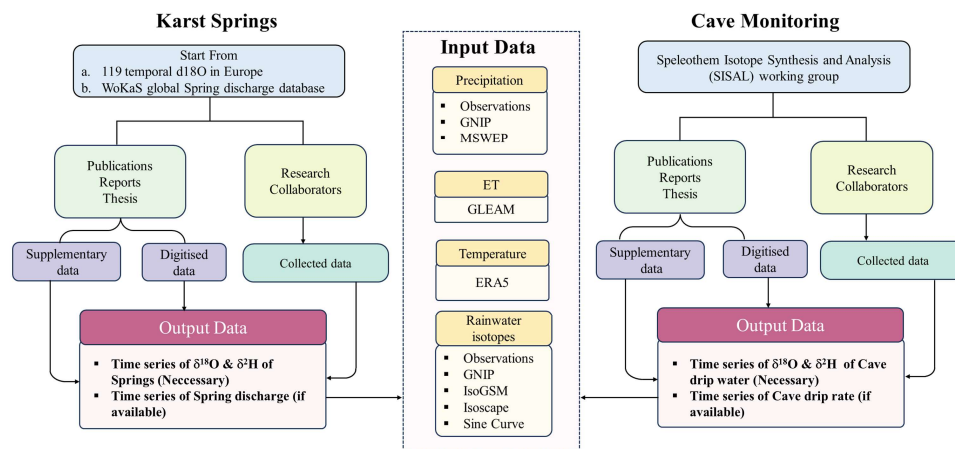
152 To allow more a broader application and comparative studies, we developed the WoKaS-Iso - a global compilation of the time
153 series of stable isotope ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) records from karst springs and cave drip water. As complementary information, this
154 database also includes the karst discharge, drip rate, precipitation, and precipitation $\delta^{18}\text{O}$ and $\delta^2\text{H}$ observations. For springs,
155 datasets were aggregated from collaborators, reviewed publications, technical reports and theses. For caves, data were sourced
156 from the SISAL_mon_v1 cave drip monitoring database (Treble et al., to be submitted), under consistent formatting and quality
157 control. Metadata considered karst springs and cave name, geological information of sites, monitoring starting and ending date,
158 observation length and data source details. We present the methodology of WoKaS-Iso database construction, describe datasets
159 records, datasets quality control, data usage notes, and discuss its applications and outlook. Furthermore, we evaluate the
160 performance of three global precipitation isotope models, offering the perspectives of model selection in karst hydrology.

161 **2 Data records and methodology**

162 The WoKaS-Iso database is built upon the foundational WoKaS (World Karst Spring hydrograph) database, the first global
163 repository of karst discharge records encompassing over 400 karst springs (Olarinoye et al., 2020). WoKaS-Iso extends this
164 framework by comprising stable isotope data ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) for karst springs, initially developed from a compilation of 119
165 stable isotope time series from Europe (Hartmann et al., 2021), the database now aims to expand this initiative to a global scale.
166 For extending the spring isotopes dataset with cave drip water isotopes and drip rate observations, and corresponding rainfall
167 observations, we collaborated with the SISAL (Speleothem Isotope Synthesis and Analysis) working group
168 (<https://pastglobalchanges.org/science/wg/sisal/intro>). Data acquisition relied primarily on the SISAL_mon_v1 cave drip water
169 database (Treble et al., to be submitted), supplemented by additional processing efforts within the WoKaS-Iso framework to
170 standardize and structure all drip-water time series and rainfall datasets for full interoperability and cross-referencing with the
171 broader WoKaS-Iso framework. In total, 66 cave sites originating from SISAL_mon_v1, together with newly integrated cave
172 monitoring sites from other published and contributed sources were standardized following the WoKaS-Iso data scheme.
173 WoKaS-Iso also synthesizes paired hydrological and climatic parameters datasets including karst spring discharge, rainfall,
174 and rainwater isotopes to support interpretation of the water isotope signature. These datasets were gathered from peer-
175 reviewed publications, theses, reports and research collaborators. In addition to site-based observations, we integrated
176 modelled climatic datasets from gridded global products, including precipitation amount (MSWEP), air temperature (ERA5),
177 evapotranspiration (GLEAM), and precipitation isotopes models (IsoGSM, Isoscape, Sine Curve). Where observed data were
178 unavailable, the precipitation amount and precipitation isotopes from nearby GNIP stations were used as substitutes.



179 From a modelling perspective, the datasets in WoKaS-Iso are organized in two main categories: **system output data** (spring
 180 isotopes, spring discharge, cave drip isotopes, cave drip rate) and **system input data** (precipitation amounts, precipitation
 181 isotopes). The overview workflow of WoKaS-Iso database creation is illustrated in Fig. 1.
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183
 184 **Figure 1:** Workflow of the karst spring and cave drip water stable isotopes database construction

185 **2.1 System output data**

186 **2.1.1 Available data types**

187 The WoKaS-Iso database compiles observations of oxygen ($\delta^{18}\text{O}$) and hydrogen ($\delta^2\text{H}$), expressed in delta (δ) notation relative
 188 to the Vienna Standard Mean Ocean Water (VSMOW), from 236 karst springs and 74 caves accommodating in total 365 drip
 189 observation points (e.g., different speleothems). In addition, WoKaS-Iso includes associated karst spring discharge, cave drip
 190 rate, precipitation amounts observations and precipitation isotope observations for karst springs and cave sites. Table 1 details
 191 the number of time series included in the database for various variables.

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Table 1: Summary of WoKaS-Iso database observations

Variables	Karst Springs	Cave Drips	Total
$\delta^{18}\text{O}$ Time Series	232	339	571
$\delta^2\text{H}$ Time Series	147	279	426
Flow Rate Time Series	122	186	308
Precipitation Amounts	119	58	177
Precipitation Isotopes	122	66	188

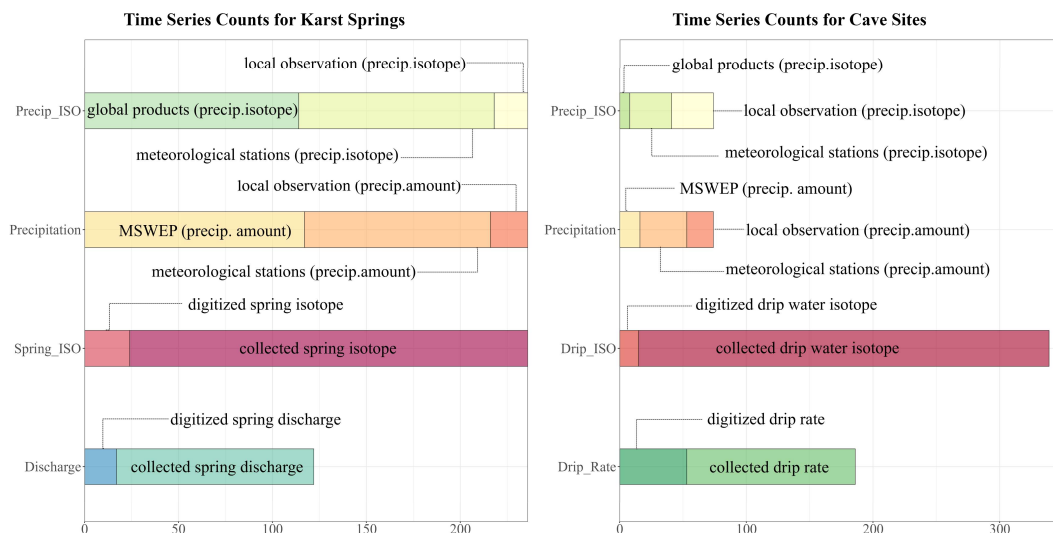
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205 Among 236 karst springs, 122 (52%) are accompanied by discharge data. Of these, 95 springs include both discharge and
206 output $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data, while 27 springs possess discharge data paired with either $\delta^{18}\text{O}$ or $\delta^2\text{H}$ measurements. The remaining
207 114 springs (48%) include only output isotope data: 48 springs with both $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data, and 66 with either $\delta^{18}\text{O}$ or $\delta^2\text{H}$
208 data. Within 74 caves, one cave includes input data alone but lacks output data. 73 caves comprise 365 drip sites, among these,
209 161 drip sites (44%) combine drip rate with drip water isotope data, of 161 drip sites, 154 drip sites have drip rate along with
210 $\delta^{18}\text{O}$ and $\delta^2\text{H}$ measurements, while 7 drip sites have drip rate and only $\delta^{18}\text{O}$ data. Additionally, 25 drip sites (7%) were measured
211 containing drip rate only. Furthermore, 178 drip sites (49%) contain drip water isotope data alone, 125 drip sites with both
212 $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data, 53 drip sites with $\delta^{18}\text{O}$ only. In addition, the database includes 122 time series of rainwater isotopes, and
213 119 time series of rainfall associated with karst springs, as well as 66 time series of rainwater isotopes and 58 time series of
214 rainfall associated with cave sites. The complete list of karst springs and caves included in the database, along with their
215 coordinates and referenced literatures, are presented in Table S1 and Table S2 in the supplement.

216 2.1.2 Origin of the collected data

217 Fig.2 illustrates the sources of the karst spring and cave drip data, respectively. For the karst springs, 90% isotopes data are
218 raw observations while 10% are digitized (extracted from a reference paper). The corresponding karst spring discharge data
219 consists of 86% raw data from collaborators, WoKaS discharge database or online open-access national database. For the
220 rainwater isotopes, 8% of the data are from local measurements, 44% from weather stations, and 48% from global isotope
221 model products. Besides, 50% rainfall data are sourced from local and meteorological data. In terms of cave drip waters, 96%
222 of drip water isotopes derive from direct field measurements, with only 4% digitized. A parallel distribution is observed for
223 drip rate records, where 72% source from observations. In case of rainwater, the majority of rainwater isotopes are obtained
224 from both local sampling campaigns and meteorological stations, with approximately 45% originating from local observations.
225 Likewise, 78% of rainfall data are acquired from local records and meteorological station datasets.

226



227
 228 **Figure 2:** Distribution of time series counts for hydrological and isotopic datasets in WoKaS-Iso database, categorized by source types. For
 229 karst springs, precipitation isotopes come from local observations (18), meteorological stations (104), and global model products (114),
 230 while precipitation amounts come from local observations (20), meteorological stations (99), and MSWEP (117). Spring water isotopes
 231 include collected (212) and digitized (24) data, and spring discharge includes collected (105) and digitized (17) data. For caves, precipitation
 232 isotopes come from local observations (33), meteorological stations (33), and global model products (8). Cave drip water isotopes include
 233 collected (324) and digitized (15) data, and cave drip rates include collected (133) and digitized (53) data.
 234

235 **Karst Springs:** the time series of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ output data were collected from (1) published data in peer-reviewed literatures,
 236 scientific reports and academic theses; (2) research collaborators from the network. **Published data:** The publications
 237 containing stable isotopes time series data for karst springs were identified through systematic searches of academic databases
 238 and web search engines using targeted keywords (e.g. “karst spring isotopes”). Some isotope datasets were obtained directly
 239 from the supplementary documents accompanying these publications. For the data not readily accessible, requests were sent
 240 to the corresponding authors to solicit contributions to the database. In cases where no response was received, the datasets
 241 were digitized from figures in scientific articles, reports and theses using WebplotDigitizer (Rohatgi, 2025), a web-based open-
 242 source tool for data extraction. To maximum digitization accuracy, high-quality figures in articles were retrieved
 243 programmatically. The extracted datasets were then visually validated by replotting and comparing them with the original
 244 figures to ensure the trends’ consistency. **Research collaborators:** To further enrich the WoKaS-Iso database, additional data
 245 were acquired through communications with research project partners and institutional collaborations. Advertisements were



246 disseminated to relevant academic departments, organizations and researchers. Furthermore, calls for contribution were made
247 to the karst community through poster and oral presentations during the international conferences and workshops. In addition
248 to the sources above, the corresponding karst discharge data were obtained from the online national database such as the U.S.
249 Geological Survey (USGS)'s National Water Information System, and Austria's Bundesministerium für Nachhaltigkeit und
250 Tourismus (eHYD) database.

251 **Cave Monitoring:** The compilation of cave drip water isotopes and drip rate for the WoKaS-Iso database followed a structured
252 workflow analogous to that of karst springs. In collaboration with SISAL (Kaushal et al., 2024), data acquisition primarily
253 drew upon the SISAL_mon_v1 (Treble et al., to be submitted), which provided a key foundation for this component. GNIP
254 station data excluded from SISAL_mon_v1 (as noted in the SISAL workbooks) are retained in WoKaS_Iso to preserve the
255 completeness and representativeness of the original monitoring datasets. For some caves, SISAL_mon_v1 includes only the
256 drip water isotope data provided by the authors, but the original drip rate measurements were not available. To address this,
257 WoKaS-Iso digitized the drip rate information from figures in the publications and incorporated these data into the database,
258 thereby enabling quantitative analyses of cave hydrology, drip water dynamics, and speleothem formation processes.
259 Furthermore, additional cave monitoring sites, independent of SISAL_mon_v1, have been incorporated from published studies
260 and research collaborators. All cave drip water datasets were systematically standardised and additional quality control
261 according to the WoKaS-Iso protocol (see chapter 4) was applied. For datasets originating from SISAL_mon_v1, this quality
262 control focused on additional harmonisation and alignment with the WoKaS-Iso structure, building on the quality control
263 already performed in Treble et al. (to be submitted). The datasets were then organised within a structure specifically designed
264 to ensure interoperability with the broader WoKaS-Iso. To ensure transparency and facilitate cross-referencing, the
265 corresponding SISAL_mon_v1 cave identifiers are provided in the WoKaS-Iso metadata tables where applicable. Additional
266 information on the cave drip water data collection methodology and site selection in SISAL_mon_v1 is provided in Treble et
267 al. (to be submitted).

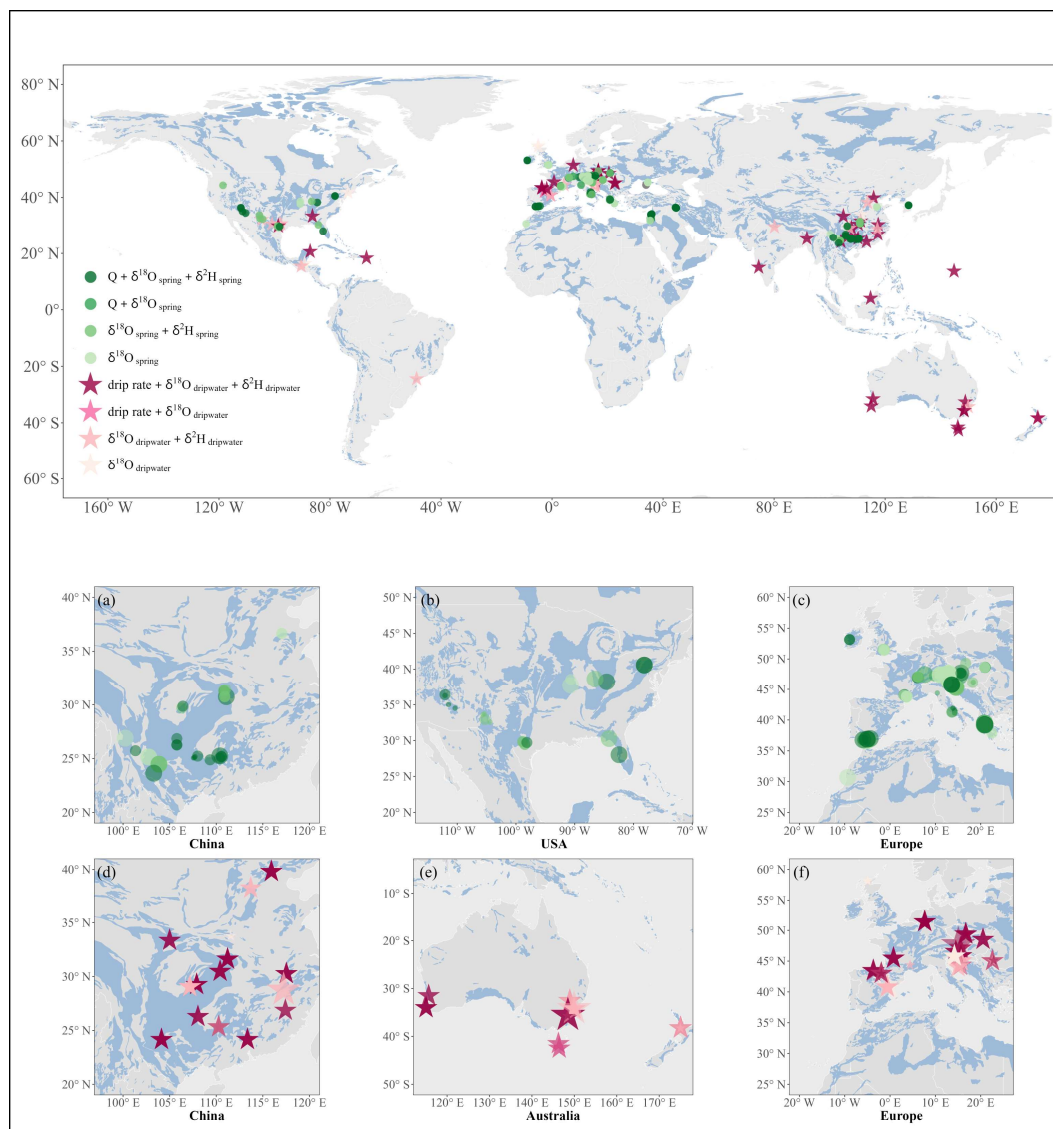
268 2.1.3 Description of available datasets

269 The spatial distributions of springs and caves within the database are shown in Fig.3 together with the World Karst Aquifer
270 Map (WOKAM) (Chen et al., 2017). The locations in the database are primarily situated across key global karst regions
271 including China, Europe, Australia, the Middle East and the USA. We summarised the detailed statistics of data type
272 combinations of 236 springs and 339 cave drip sites with isotopic data records in Fig.4, stratified by the predominant karst
273 areas identified in Fig.3. Springs are analysed for China, the USA, Europe for springs, while cave drip sites are grouped by
274 China, Australia, and Europe. The stacked histograms display the distribution of dataset types across these regions and align
275 with the regional distribution trend described in the preceding section.

276 Most of karst spring records are collected in Europe with approximately 50% of them accompanied by discharge measurements
277 (Fig. 4a). Fewer springs, but a similar composition of the records is observed in China, where roughly half of the spring
278 locations include discharge data. Whereas only about one-third of springs in the USA have associated discharge data. For karst



279 springs in other regions, the proportion with discharge data is higher, up to 83%. As for isotopic time series, portions of spring
280 datasets containing both $\delta^{18}\text{O}$ and $\delta^2\text{H}$ is 86% in China, 70% in the USA and 62% in other countries. Fig. 4b shows that the
281 majority of cave drip sites in China include drip rate observations. Almost half of the drip sites in Australia and Europe
282 incorporate drip rate data, while the proportion is lower in other regions (only around 30%). Furthermore, more than 95% cave
283 drips were measured for both $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data in China and Australia; the proportion exceeds 70% in Europe and other
284 regions.
285

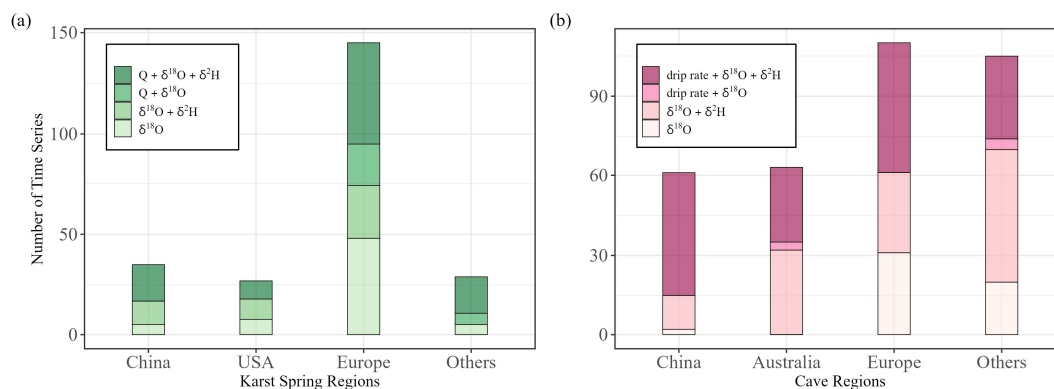


286
 287

288 **Figure 3:** Geographic distribution of karst springs and cave sites included in the WoKaS-Iso database, along with the types of data available
 289 at each site. Blue areas indicate karst regions from the World Karst Aquifer Map (WOKAM, Chen et al. 2017). “Q” in the legend refers to



290 karst spring discharge. ‘Green round’ symbols represent karst springs; ‘red star’ symbols represent caves. The symbol color intensity reflects
 291 the richness of available data combinations at each site, categorized into four subgroups: **flow rate+ $\delta^{18}\text{O}$ + $\delta^2\text{H}$** , **flow rate+ $\delta^{18}\text{O}$, $\delta^{18}\text{O}$ +
 292 $\delta^2\text{H}$, $\delta^{18}\text{O}$** , with darker color indicating more comprehensive datasets including both hydrological and isotopic data. Panels (a), (b), and (c)
 293 show zoomed-in maps of karst springs in China, the USA, and Europe, respectively. Panels (d), (e), and (f) show zoomed-in maps of cave
 294 sites in China, Australia, and Europe. In the zoomed maps, the size of each symbol presents the sampling resolution of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ time
 295 series at each spring and cave drip site. The temporal resolution is categorized into three classes: **less than biweekly, monthly and coarser
 296 than monthly**, corresponding to large, medium and small markers respectively.



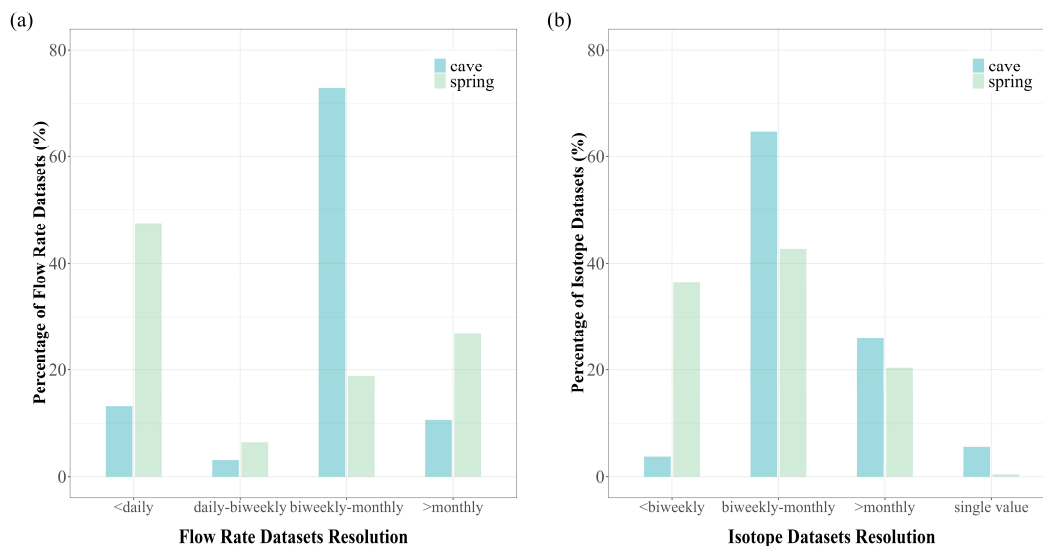
297
 298 **Figure 4:** Summaries of data types across the major karst regions for (a) karst springs and (b) cave drip water sites. In panel (a), “Q” in the
 299 legend represents karst spring discharge.

300
 301 Stable isotopes in spring discharge and drip waters can show strong seasonal variability due to fluctuations in precipitation,
 302 and temperature under changing climatic conditions. Adequate temporal resolutions are necessary to quantify these seasonal
 303 dynamics in detail and capture short-term hydrological patterns during rainfall or snowmelt events. Information about the
 304 temporal resolution of the available datasets is given in the regional maps in Figs 3a-f. For karst springs, Figs 3abc indicate
 305 that the sampling interval at most springs in China was at a monthly time scale. The resolution of springs in the USA is
 306 distributed evenly at monthly to coarser resolution. In Europe, 52 springs were monitored at a resolution of less than biweekly
 307 and 67 springs were visited at monthly resolution; only a small part of springs have coarser resolution. For the cave drip sites
 308 (Figs 3def), there are 90% cave drip isotopes at monthly sampling intervals in China, 56% in Australia as well as 70% in
 309 Europe. In contrast, the percentage of finer than biweekly is lower than 6% in any of three targeted regions.

310 A general overview of available temporal resolution is provided in Fig.5. Nearly 50% of spring discharge datasets have a high
 311 resolution of finer than daily, and over 12% cave drip rate datasets situated in the same class (Fig 5a). The dominant resolution
 312 of cave drip rate falls between biweekly and monthly, reaching around 74%, whereas the resolutions of spring discharge
 313 datasets are more evenly spread across four categorized resolution classes. However, a noticeable portion of spring discharge
 314 datasets exceed the monthly interval. For the stable isotope records from springs and cave drips, the primary resolution is



315 within biweekly-to-monthly range, accounting for around 64% of cave drip isotope datasets and over 40 % of spring data.
316 Furthermore, 36% of isotope datasets from karst springs were measured at a resolution finer than biweekly. For cave drip sites,
317 27 % records were sampled at the coarser-monthly interval.



318 **Figure 5:** (a) Proportions of temporal resolution categories of discharge and drip rate datasets for karst springs and cave drip sites; The
319 datasets are divided into four resolution levels: **finer than daily, daily to biweekly, biweekly to monthly and coarser than monthly**. (b)
320 Proportions of temporal resolution categories of stable isotopes for karst springs and caves. The resolutions are stratified into four categories:
321 **finer than biweekly, biweekly to monthly, coarser than monthly and single-value records**.
322

323 2.2 System input data

324 2.2.1 Available data types

325 The WoKaS-Iso database includes the precipitation amount and precipitation $\delta^{18}\text{O}$ and $\delta^2\text{H}$ observations for karst springs and
326 cave sites, compiled from the same sources described in subsection 2.1.2 (also see Table 1 & Figure 2). To ensure adequate
327 spatial and temporal coverage, karst springs and cave sites lacking local rainfall and rainwater isotopes records were
328 supplemented with the data from Global Network of Isotopes in Precipitation (GNIP) database. Firstly, the geographic
329 coordinates of karst springs, cave sites, and GNIP stations within the related countries were imported into ArcGIS where the
330 closest GNIP station to each karst spring and cave site was identified. Secondly, the distances between the springs or caves
331 and their nearest GNIP stations were measured using ArcGIS. With the aim of reflecting representative of the local climatic
332 and isotopic characteristics for karst springs and caves, only GNIP stations within 25 km were retained.



333 For karst springs, 20 sites possess local rainfall measurements, and 99 springs derive precipitation data from nearby
334 meteorological stations including GNIP stations, while the remaining 117 springs lack rainfall data. Regarding precipitation
335 isotope observations, only 18 springs are with auxiliary local isotope data, 104 springs use the data from meteorological or
336 GNIP network, and 114 springs have no related isotope records. For cave sites, 21 caves include locally measured rainfall, 37
337 caves obtained rainfall data from adjacent weather stations, and 16 caves without rainfall records. As for precipitation isotopes,
338 33 caves are associated with local measurements, 33 caves rely on weather stations-based isotope datasets or GNIP-derived
339 data, and 8 caves lack isotope observations. To offer comprehensive metadata for input observations, the distance from the
340 precipitation and precipitation isotopes sampling sites to cave/spring sites were calculated where geographic coordinates were
341 available, documented in the metadata tables for spring input and cave input datasets.

342 Since datasets on precipitation amount and precipitation $\delta^{18}\text{O}$ and $\delta^2\text{H}$, observed locally or provided by GNIP, were not
343 available at all or output locations or limited in their temporal extent, the WoKaS-Iso database includes complementary datasets
344 from six global products for continuous rainfall, precipitation $\delta^{18}\text{O}$ and $\delta^2\text{H}$, air temperature as well as both actual and potential
345 evapotranspiration. The information of these global products used in this study are listed in Table 2, including relevant
346 modelled variables, time span, spatial and temporal resolution and the source for the construction of models.

347 Precipitation data were obtained from MSWEP v2.8 (Beck et al., 2017, 2019a, b), a multi-source ensemble product offering
348 daily and monthly estimates at 0.1° resolution from 1979–2020. MSWEP improves global precipitation accuracy by combining
349 gauge, satellite, and reanalysis data using a weighted ensemble based on network density and local performance (Liu et al.,
350 2019). Evaporation estimates were sourced from GLEAM v4.1a (Hulsman et al., 2023; Koppa et al., 2022; Martens et al.,
351 2017; Miralles et al., 2011, 2025; Zhong et al., 2022), which integrates satellite data and physical modelling with machine
352 learning to estimate daily and monthly actual and potential evaporation at 0.1° resolution from 1980–2023. Air temperature
353 time series were extracted from ERA5, the fifth-generation atmospheric reanalysis developed by ECMWF (Hersbach et al.,
354 2020, 2023), which provides consistent daily climate data since 1940 at 0.25° resolution using 4D-Var data assimilation
355 technique and the CY41R2 forecasting system. To characterize precipitation isotope variability, we used monthly $\delta^{18}\text{O}$ and
356 $\delta^2\text{H}$ outputs from IsoGSM (Kanamitsu et al., 2002; Nan et al., 2021; Yoshimura et al., 2008), a general circulation model
357 incorporating isotopic fractionation and nudged with NCEP (National Centres for Environmental Prediction) reanalysis data,
358 covering 1979–2021. Additionally, long-term spatial isotope patterns were derived from the Isoscape product (etopo5, 2025;
359 Bowen et al., 2005; Bowen and Revenaugh, 2003; Bowen and Wilkinson, 2002), which interpolates GNIP data using
360 topographic and geographic predictors at a 5-arcminute resolution. Finally, seasonal isotope dynamics were represented using
361 the sinusoidal precipitation isotope model (Allen et al., 2019), which fits annual sine curves to global precipitation isotope
362 records and maps the resulting parameters to derive daily and monthly isotope predictions from 60°S to 90°N . Together, these
363 products provide a consistent climatological and isotopic framework for interpreting site-level karst and cave hydrology.

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Table 2: Information of the global products included in the WoKas_Iso database

Variable	Model Name	Data Source	Spatial Resolution	Temporal Resolution	Spatial Coverage	Time Coverage	Reference
Precipitation	MSWEP ¹ v2.8	Gauge, Satellite, Reanalysis	0.1°	Daily/Monthly	Global	1979–2020	(Beck et al., 2019b)
Precipitation isotopes	IsoGSM ²	Reanalysis	200 km	Monthly	Global	1979–2021	(Yoshimura et al., 2008)
Precipitation isotopes	Isoscape	GNIP ⁴	5 arcmin	Monthly	Global	Jan–Dec	(Bowen et al., 2005)
Precipitation isotopes	Sine Curve	GNIP, CNIP ⁵ , USNIP ⁶	5 arcmin	Daily/Monthly	60°S– 90°N	Jan–Dec	(Allen et al., 2019)
Air temperature	ERA 5	Reanalysis	31 km	Daily/Monthly	Global	1940–2024	(Hersbach et al., 2023)
Evapotranspiration	GLEAM ³ 4.1a	Satellite, Reanalysis	0.1°	Daily/Monthly	Global	1980–2023	(Miralles et al., 2025)

368 ¹Multi-Source Weighted-Ensemble Precipitation ⁵Canadian Network for Isotopes in Precipitation

369 ²Isotopes-integrated Global Spectral Model ⁶US Network for Isotopes in Precipitation

370 ³Global Land Evaporation Amsterdam Model

371 ⁴Global Network of Isotopes in Precipitation

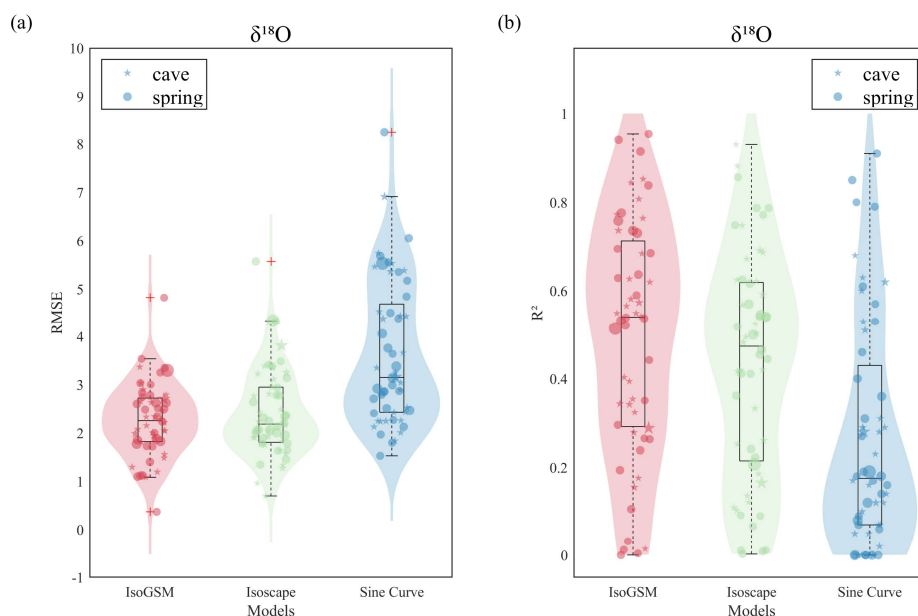
372 2.2.2 Evaluation of different precipitation isotope data

373 While global precipitation and evapotranspiration data were evaluated with observations in their original studies (see Table 2),
 374 an evaluation of the isotopic composition of rainfall provided by the three precipitation isotope models—IsoGSM, Isoscape,
 375 and the Sine Curve model, is still required. For that, we compared monthly simulated precipitation $\delta^{18}\text{O}$ and $\delta^2\text{H}$ against site-
 376 specific observations from both cave drip water and karst spring locations. For precipitation $\delta^{18}\text{O}$ comparison, a total of 55



377 sites were analysed comprising 26 cave locations, 15 spring locations and 14 nearby meteorological stations to compensate the
378 limited availability of isotopic measurements at spring locations. For sites with daily precipitation, the monthly amount-
379 weighted precipitation isotopes were calculated, while for sites lacking daily precipitation, the stepwise interpolation of
380 precipitation isotopes was applied to derive monthly means. The same analysis was done for $\delta^2\text{H}$ (provided in supplement
381 section S2).

382 We quantified the agreement of the global products and the observed isotopic composition of precipitation by the root-mean-
383 square error (RMSE) and the coefficient of determination (R^2). Fig.6 presents the performance metrics in predicting $\delta^{18}\text{O}$.
384 Based on RMSE, IsoGSM displays the lower median RMSE value ($\sim 2\%$) with a narrow interquartile and minimum outliers,
385 indicating the most consistent predictions across both caves and springs. The Isoscape model exhibits a comparable median
386 RMSE, though with a greater variability and higher outliers, reflecting less robustness. In contrast, the Sine Curve model yields
387 the highest median error ($>3\%$) and broader distributions, highlighting significantly inferior performance. Concerning R^2 ,
388 IsoGSM achieves the highest median R^2 (~ 0.6), however, its R^2 values span a wide range. The Isoscape model, having a
389 slightly lower median R^2 value (~ 0.5), shows a tighter distribution. The Sine Curve model performs worst, with median R^2 less
390 than 0.2 and a concentration of low values, indicating poor explanatory power.



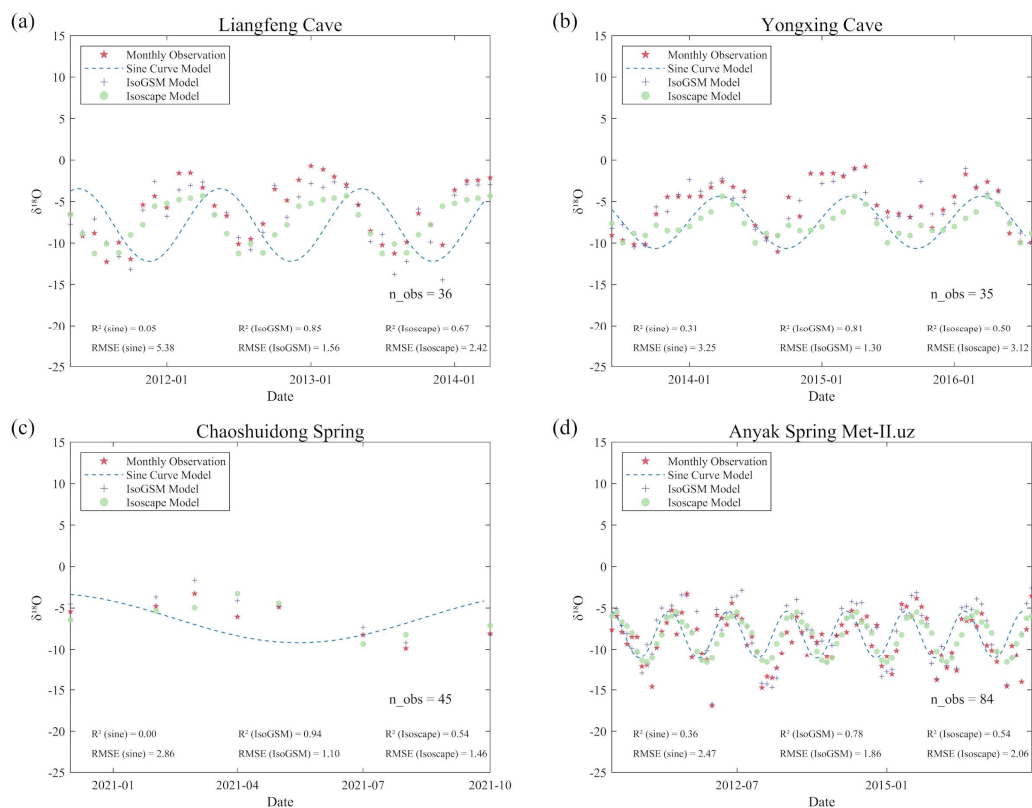
391
392 **Figure 6:** Statistical comparison of three model performance for $\delta^{18}\text{O}$ in precipitation at cave (stars) and springs sites (circles). (a) Root
393 Mean Square Error (RMSE); (b) Coefficient of determination (R^2). Violin plots show the distribution of performance metrics for each model:



394 IsoGSM (red), Isoscape (green), and Sine Curve (blue). Boxplots within violin indicate the median, interquartile range and outliers. Lower
395 RMSE and higher R^2 indicate better model performance.

396 **To evaluate the different performances of the global datasets**, we compare time series of observed monthly $\delta^{18}\text{O}$ and $\delta^2\text{H}$
397 with model outputs from the Sine Curve, IsoGSM, and Isoscape models across all selected locations. Fig. 7 shows the $\delta^{18}\text{O}$
398 comparisons at four representative sites: Liangfeng Cave, Yongxing Cave, Chaoshuidong Spring and the Met-II.uz
399 meteorological station near Anyak Spring (see supplement Section S1 for a complete comparison for other 51 sites). Overall,
400 the Sine Curve model shows limited ability in reproducing the temporal course of the observations. In contrast, the IsoGSM
401 model closely aligns the observed $\delta^{18}\text{O}$ dynamics at four sites, yielding high R^2 values (0.85, 0.81, 0.94 and 0.78 for Liangfeng
402 Cave, Yongxing Cave, Chaoshuidong Spring and the Met-II.uz meteorological station near Anyak Spring, respectively)
403 alongside relatively low RMSE values, which reflects robust performance in both correlation and prediction accuracy. The
404 Isoscape model attains moderate predictions with R^2 exceeding 0.5 at all four sites. Although it outperforms the Sine Curve
405 model, it tends to be less reliable than IsoGSM in capturing the isotopic variability. A similar comparison is also performed
406 for $\delta^2\text{H}$ (see supplement section S2) indicating similar performances of the global products with IsoGSM showing slightly
407 superior performances over Isoscape and pronounced superior performance over the Sine Curve model. Different phase shifts
408 between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in their Sine Curve model indicate a poor representation of their physical covariance which is given
409 through the global/local meteoric waterline. Overall, IsoGSM provides the most accurate and robust $\delta^{18}\text{O}$ predictions, for
410 which reason we recommend it for those cave and spring locations where no local observations are available.

411



412
 413 **Figure 7:** Time series comparison of modelled and observed monthly $\delta^{18}\text{O}$ in precipitation at two cave sites (a–b) and two spring sites (c–
 414 d). Observations (red stars) are compared with estimates from the Sine Curve model (dashed blue line), IsoGSM (purple crosses), and the
 415 Isoscape model (green circles). Each panel shows the number of monthly observations (n.obs) and model performance statistics (R^2 and
 416 RMSE).

417 3 Database structure and usage notes

418 The datasets compiled in the WoKaS-Iso database are publicly archived as a zipped package titled “WoKaS_Iso_Data_Records”
 419 in OPARA, an open-access repository of research data from Saxon Universities (<https://doi.org/10.25532/OPARA-909>; Zang,
 420 2025). The zip file is organized into three main folders: WoKaS_Iso_Input_Data, WoKaS_Iso_Output_Data,
 421 Global_Products_Data. Each folder is subdivided into several subfolders, with their structure and contents described in the
 422 following section:



423 **3.1 WoKaS_Iso_Input_Data**

424 Contains precipitation amount and precipitation isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) metadata tables and corresponding datasets for karst
 425 springs and cave sites:

- 426 **i. WoKaS_Iso_Spring_Input_Metadata** provides summarised information on the precipitation and precipitation
 427 isotopes sites associated with each spring included in the database. Each spring is assigned a unique identifier as
 428 *wokas_iso_id*, which is constructed by using ISO country code (e.g., *AT* for Austria), a data type indicator (*S* for
 429 spring and *C* for cave) and a serial number (e.g., *AT-S-0001*). Some springs are associated with multiple precipitation
 430 or precipitation isotopes sites sharing the same *wokas_iso_id*, but each site is assigned its own
 431 *precipitation_entity_name* and *precip_iso_entity_name* as keys to link the metadata with their corresponding dataset.
 432 Furthermore, the *precip_distance_to_spring* and *precip_iso_distance_to_spring* indicate the distance in meters from
 433 each site to the specific spring. This structure allows users to flexibly select the desirable sites for their use. The full
 434 list of variables included in the spring input metadata table are explained in the Table 3.
- 435 **ii. WoKaS_Iso_Spring_Input_Datasets** consists of 135 csv files. Each csv file represents the time series of
 436 precipitation amount and precipitation $\delta^{18}\text{O}$ and $\delta^2\text{H}$ for a specific spring. The csv file naming format is *Input-*
 437 *wokas_iso_id@spring_name* (e.g., *Input-AT-S-0002@Wasseralmquelle(A)*). Each csv file contains *wokas_iso_id*,
 438 *precipitation_entity_name*, *date_precip* (precipitation observation date), *precipitation*, *unit* (precipitation amount
 439 unit), *precip_iso_entity_name*, *date_precip_iso* (precipitation isotopes sampling date), *d18O*, *dD* and *note*.
- 440 **iii. WoKaS_Iso_Cave_Input_Metadata** offers metadata summaries for cave sites input data, structured in the same
 441 way as the spring input metadata table. Similarly, each cave identifier is assigned to the cave site consisting of the
 442 ISO country code, the cave data type indicator *C* and its serial number (e.g., *AT-C-0001*). The entity name and distance
 443 fields align with the same conventions as springs. All variables are consistent with those used for spring metadata and
 444 are presented in Table 3.
- 445 **iv. WoKaS_Iso_Cave_Input_Datasets** contains 67 csv files; each refers to a specific cave site. The csv file naming
 446 convention and internal structure follow the same pattern (e.g., *Input-AT-C-0001@Obir Cave*) as described in the
 447 spring input datasets section.

448 **Table 3:** Description of variables in the spring/cave input data metadata files

Variable	Description	Variable	Description
country	country the spring /cave is in	precip_iso_distance_to_sprin g/cave (m)	distance between precipitation isotope site and spring/cave (m)
wokas_iso_id	WoKaS-Iso identifier	precip_iso_enentity_name	identifier assigned to precipitation isotopes site linked to a specific spring/cave
sisal_monv1_id/woka s_id	cave/spring identifier in SISAL_monv1/WoKaS database	precip_iso_latitude	precipitation isotopes measurements site latitude in decimal degrees. (N+, S-)



spring/cave_name	spring/cave name	precip_iso_longitude	precipitation isotopes measurements site longitude in decimal degrees. (E+, W-)
precipitation_site_name	location of precipitation measurements	precip_iso_elevation	meters above mean sea level
precip_distance_to_spring/cave(m)	distance between precipitation site and spring/cave	precip_d18O_start_date	start day of the oxygen-18 measurement in rainwater sample(dd/mm/yyyy)
precip_entity_name	identifier assigned to precipitation site linked to a specific spring/cave	precip_d18O_end_date	end day of the oxygen-18 measurement in rainwater sample(dd/mm/yyyy)
precip_latitude	P site latitude in decimal degrees. (N+, S-)	precip_d18O_observation_length	number of oxygen-18 measurements in rainwater
precip_longitude	P site longitude in decimal degrees. (E+, W-)	precip_dD_start_date	start day of the deuterium measurement in rainwater sample(dd/mm/yyyy)
precip_elevation	meters above mean sea level	precip_dD_end_date	end day of the deuterium measurement in rainwater sample(dd/mm/yyyy)
precipitation_start_date	start day of precipitation measurement(dd/mm/yyyy)	precip_dD_observation_length	number of deuterium measurements in rainwater
precipitation_end_date	end day of precipitation measurement(dd/mm/yyyy)	precip_iso_data_source	isotopic datasets in precipitation from who or where
precip_observation_length	number of precipitation measurements	reference	relevant literatures
precip_data_source	precipitation datasets from who or where	additional information	free-text column
precip_isotopes_site_name	location of precipitation Isotopes measurements		

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 450

451 3.2 WoKaS_Iso_Output_Data

452 Includes output metadata tables and output datasets for karst springs and cave drip sites:

- 453 i. **WoKaS_Iso_Spring_Output_Metadata** summarizes attributes for karst springs documented in the WoKaS-Iso
- 454 database including the geographic information of springs, an overview of karst spring discharge and isotopes for each
- 455 spring. Each spring has the consistent identification through unique *wokas_iso_id*, same identifier used in the spring
- 456 input data records. In the same way, the specific fields *discharge_entity_name* and *isotope_entity_name* are designed
- 457 to establish the connection to their corresponding datasets. The complete list of parameters contained in the spring
- 458 output metadata table are shown in Table 4.



459 ii. **WoKaS_Iso_Spring_Output_Datasets** presents karst spring discharge, $\delta^{18}\text{O}$ and/or $\delta^2\text{H}$ datasets for 236 springs,
 460 organized as separate 236 csv files. Every csv file follows a standardized naming format “*Output-*
 461 *wokas_iso_id@spring_name*” (e.g., *Output-AT-S-0002@Wasseralmquelle(A)*). The uniform internal structure of
 462 workbook includes the following columns: *wokas_iso_id*, *discharge_entity_name*, *date_discharge* (measurements
 463 date), *discharge*, *discharge_unit* (the unit of discharge), *iso_entity_name*, *date_iso* (isotope data sampling date), *d18O*
 464 and *dD*.

Table 4: Description of variables in the spring output metadata table

Variable	Description	Variable	Description
country	country the spring is in	discharge_data_source	spring discharge datasets from who or where
wokas_iso_id	WoKaS-Iso identifier	isotope_entity_name	identifier assigned to link the metadata to its isotopic datasets
wokas_id	spring identifier in WoKaS database	d18O_start_date	start day of oxygen-18 data collection of spring water sample(dd/mm/yyyy)
spring_name	spring name	d18O_end_date	end day of oxygen-18 data collection of spring water sample(dd/mm/yyyy)
latitude	spring latitude in decimal degrees. (N+, S-)	d18O_observation_length	number of oxygen-18 measurements
longitude	spring longitude in decimal degrees. (E+, W-)	d2H_start_date	start day of deuterium data collection of spring water sample(dd/mm/yyyy)
elevation(m)	meters above mean sea level	d2H_end_date	end day of deuterium data collection of spring water sample(dd/mm/yyyy)
type	spring	d2H_observation_length	number of deuterium measurements
discharge_entity_name	identifier assigned to link the metadata to its discharge datasets	isotope_data_source	spring isotopic datasets from who or where
discharge_start_date	start day of spring discharge measurement(dd/mm/yyyy)	reference	relevant literatures
discharge_end_date	end day of spring discharge measurement(dd/mm/yyyy)	additional_information	free-text column
discharge_observation_length	number of spring discharge observations		

467
 468 iii. **WoKaS_Iso_Cave_Output_Metadata** comprises a comprehensive overview of cave drip rate and cave drip isotopic
 469 records ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) for all cave drip sites. Each cave includes multiple drip sites which are assigned the same
 470 *wokas_iso_id* which is assigned in the cave input section but are distinguished by the unique *drip_rate_entity_name*



471 and *drip_iso_entity_name* entries. Explanations for each variable in the cave output meta table is presented in Table
 472 5.

473 **iv. WoKaS_Iso_Cave_Output_Datasets** contains 73 csv files. Each csv file stores the drip rate and drip isotopes
 474 datasets for the individual cave. The csv file name follows the format *Output-wokas_iso_id@cave_name* (e.g.,
 475 *Output-AT-C-0001@Obir Cave*). Within each csv, multiple drip sites are documented using their unique entity names.
 476 The content includes the columns: *wokas_iso_id*, *drip_rate_entity_name*, *date_rate* (drip rate measurement date),
 477 *unit* (the unit of drip rate), *drip_iso_entity_name*, *date_iso* (sampling date of drip water isotopes), *d18O* and *dD*.

478
 479

Table 5: Description of variables in the cave output metadata table

Variable	Description	Variable	Description
country	where the spring is located	drip_rate_observation_length	number of cave drip rate observations
wokas_iso_id	WoKaS-Iso identifier	drip_isotopes_entity_name	assigned identifier to link the metadata to related drip water isotopic data
sisal_monv1_id	cave identifier in SISAL_monv1 database	drip_d18O_start_date	start day of oxygen-18 data collection of drip water sample(dd/mm/yyyy)
name	cave name	drip_d18O_end_date	end day of oxygen-18 data collection of drip water sample(dd/mm/yyyy)
latitude	cave latitude in decimal degrees. (N+, S-)	drip_d18O_observation_length	number of drip oxygen-18 measurements
longitude	cave longitude in decimal degrees. (E+, W-)	drip_d2H_start_date	start day of deuterium data collection of drip water sample(dd/mm/yyyy)
elevation(m)	meters above mean sea level	drip_d2H_end_date	end day of deuterium data collection of drip water sample(dd/mm/yyyy)
type	cave	drip_d2H_observation_length	number of drip deuterium measurements
drip_site	cave drip site name	data_source	drip rate and drip isotopes datasets from where or who
drip_rate_entity_name	assigned identifier to link the metadata to related drip rate data	reference	relevant literatures
drip_rate_start_date	start day of cave drip rate measurement(dd/mm/yyyy)	additional_information	free-text column
drip_rate_end_date	end day of cave drip rate measurement(dd/mm/yyyy)		

480



481 3.3 Global_Products_Data

482 Contains gridded datasets from six global models. Each product has a dedicated folder with its name WoKaS_Iso_MSWEF,
483 WoKaS_Iso_GLEAM, WoKaS_Iso_ERA5, WoKaS_Iso_IsoGSM, WoKaS_Iso_Isoscape, WoKaS_Iso_Sine_Curve,
484 WoKaS_Iso_Scripts.

- 485 • WoKaS_Iso_MSWEF, WoKaS_Iso_GLEAM, WoKaS_Iso_ERA5, WoKaS_Iso_Sine_Curve: the modelled data
486 from these products are systematically sorted into four subfolders according to location type (spring or cave) and time
487 resolution (daily or monthly). For example, WokaS_Iso_MSWEF folder includes
488 WoKaS_Iso_Daily_MSWEF_Caves, WoKaS_Iso_Daily_MSWEF_Springs, WoKaS_Iso_Monthly_MSWEF_Caves,
489 WoKaS_Iso_Monthly_MSWEF_Springs. Each subfolder contains compatible csv files storing continuous time series
490 for individual spring or cave. The csv file names adhere to a standardized naming rule, combining the product name,
491 temporal resolution, the *wokas_iso_id* and spring /cave name. For instance, *MSWEF_Daily_AT-C-0001@Obir Cave*
492 refers to the daily gridded datasets from MSWEF at Obir Cave in Austria.
- 493 • WoKaS_Iso_IsoGSM, WoKaS_Iso_Isoscape: Since IsoGSM and Isoscape provide monthly $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data only,
494 each folder is subdivided into two categories for caves and springs: WoKaS_Iso_IsoGSM/Isoscape_Monthly_Caves
495 and WoKaS_Iso_IsoGSM/Isoscape_Monthly_Springs. While, the csv file naming is slightly different from other
496 products, constructed using *IsoGSM/Isoscape_wokas_iso_id@spring/cave_name* (e.g., *IsoGSM_AT-C-0001@Obir*
497 *Cave; Isoscape_AT_C_0001@Obir Cave*).
- 498 • WoKaS_Iso_Scripts: this folder includes three MATLAB scripts developed to aid users in extracting daily and
499 monthly data from NetCDF files of MSWEF, GLEAM and ERA5. The accompanying README file offers detailed
500 instruction on how to use the scripts and the download guidelines for each product, which assists users efficiently
501 integrate authoritative gridded datasets into their workflows.

502 3.4 Usage notes

- 503 • **Metadata:** The columns *precip_data_source*, *precip_iso_data_source* (in the spring and cave input meta tables),
504 *discharge_data_source*, *isotope_data_source* (in the spring output meta table), *data_source* (in the cave output meta
505 table) specify the origins of respective data: precipitation, precipitation isotopes, discharge, spring isotopic data, cave
506 drip rate and cave drip isotopes respectively. These sources can include data contributors, or digitization from specific
507 figures or tables in publications, reports or theses, or retrieval from online repositories with links provided if
508 applicable. All meta tables include the *reference* column listing all related literature that:(1) the spring/cave drip site
509 was studied; (2) the data were originally published; (3) contained figures and tables were digitized. These references
510 enable users to get further context regarding datasets sampling method, climate conditions, hydrogeological settings
511 of the studied spring/cave system. For peer-reviewed publications, DOIs are offered, while URLs of reports or theses
512 are provided if available.



- 513 • **Machine-readability:** All csv files storing input and output datasets are designed in a machine-readable format to
514 facilitate efficient and automated data processing.
- 515 • **Link the metadata to datasets:** Each csv file name incorporates the unique *wokas_iso_id* that is organized in the
516 metadata tables. This identifier enables location of the related spring or cave dataset by matching with file name (e.g.
517 *Output-wokas_iso_id@spring_name*). Additionally, within each csv file, the entity name fields (*precip_entity_name*,
518 *precip_iso_entity_name*, *discharge_entity_name*, *isotope_entity_name*, *drip_rate_entity_name* and
519 *drip_iso_entity_name*) can work as the identified keys to connect with the corresponding metadata entries. These
520 identifiers can be utilized to retrieve specific time series data from the measurement sites of interest.
- 521 • **Global products datasets:** Model-derived data corresponding to each site are provided in CSV files named according
522 to their respective *wokas_iso_id* for easy reference. Monthly datasets, dates are separated into two columns: year and
523 month, while daily data use a single dd/mm/yyyy format. These data represent the closest grid cell to each site;
524 therefore, users should be aware of potential spatial differences when comparing with local observations. Proper
525 citation of original data sources is required when utilizing these datasets.
- 526 • **Global products scripts:** The provided scripts are designed to extract data at monthly and daily resolutions from the
527 MSWEP, GLEAM, and ERA5 datasets, corresponding to the time periods listed in Table 2. Users can apply these
528 scripts to extract data at any geographic coordinates of interest. The global product data correspond to the grid cell
529 closest to the site coordinates. Users should be aware of potential spatial mismatches. Automated data download
530 routines are not included; instructions for obtaining the required NetCDF files are provided in the accompanying
531 README file.

532 **4 Data quality control and evaluation**

533 **4.1 Data quality control**

534 A series of quality control measures were implemented throughout the large datasets synthesized in the WoKaS-Iso database
535 to ensure data precision, consistency and integrity:

536 **Site information verification:** All spring and cave drip site names, coordinates, elevation, data units, precipitation sites and
537 precipitation isotope sampling sites were initially cross-checked against the original sources: supplementary materials, tables,
538 original data contributed by collaborators or digitized from related figures. Additionally, all the time series were reviewed for
539 consistency with the original datasets, ensuring correct sampling date accurately matching its associated measurements to
540 avoid any discrepancies.

541 **Standardized formatting:**

- 542 i. **Naming convention:** All *wokas_iso_id* entries were validated to confirm conformity with the standardized naming
543 convention including verification of the ISO country code, data type indicator (C for cave and S for spring) and



544 sequential numbering within each country. The csv file names were systematically reviewed folder by folder to ensure
545 compliance with the naming patterns stated in section 3.
546 ii. CSV file structure: All files were checked to be machine-readable in comma-delimited csv format. Each csv file was
547 examined to guarantee a consistent internal structure with uniform column headers.
548 iii. Date and coordinates formatting: The dates were formatted consistently in dd/mm/yyyy across all datasets. The
549 latitude and longitude were formatted with four decimals.

550 Consistency checks:

551 i. Data consistency: The dates and corresponding time series of all datasets were checked to confirm they were sorted
552 chronologically.
553 ii. Spatial consistency: Latitude and longitude were validated to fall in valid ranges (N+, S-, E+, W-), and validation of
554 spatial distribution on map were verified by visualization.
555 iii. Metadata and datasets matching: The identifiers *wokas_iso_id*, *precip_entity_name*, *precip_iso_entity_name*,
556 *discharge_entity_name*, *iso_entity_name*, *drip_rate_entity_name* and *drip_iso_entity_name* were cross validated
557 against metadata to ensure correct linkage with the corresponding datasets. In addition, the start date, end date and
558 observation length of all time series were checked to align with actual datasets.

559 **Data source verification:** Checking data sources recorded in the meta tables was implemented to ensure proper citation and
560 traceability. The indicated figures and tables were checked to be correctly represented. All provided URLs access to online
561 database were tested to verify datasets retrieval. The DOIs (provided as web links) were confirmed working and accurately
562 linked to the cited publications. Where available, links of reports and theses were also tested for accessibility.

563 For cave drip water datasets originating from SISAL_mon_v1, WoKaS-Iso builds on the automated quality control already
564 applied in Treble et al. (to be submitted). Within WoKaS-Iso quality control, the SISAL_mon_v1 records were therefore not
565 re-processed from scratch, but underwent additional harmonisation and validation steps: mapping to the WoKaS-Iso file and
566 naming conventions, cross-checking identifiers and time ranges against the new metadata structure, and ensuring consistent
567 linkage and interoperability with associated precipitation and spring datasets and references as described in the following.

568 4.2 Data quality attribution

569 The datasets quality for each spring and cave site was assessed based on an attribution scheme assigning scores to both output
570 and input data according to their sources (Table 6). For output data, **collected spring discharge/drip rate** and **collected**
571 **spring/drip water isotope** were obtained from research collaborators, original authors, online databases or supplementary
572 materials of publications. These sources are generally of high quality and were hence assigned a score of 3. **digitized spring**
573 **discharge/drip rate** and **digitized spring/drip water isotope** were digitized from the plots in publications or reports or theses.
574 Although the extraction process was carried out as precisely as possible, some inaccuracies and uncertainties inherently
575 remained due to the resolution and temporal coverage of the original plots. Thus, the score of 2 was assigned to the digitized
576 data. For those locations without relevant data were given a score of 0. For input data, three quality levels were defined



577 according to the sources of precipitation isotopes and precipitation information: local measurements, meteorological stations
 578 and global models. The **local observation (precip. isotope/amount)** acquired from on-site monitoring, which are rare and
 579 valuable particularly for karst springs, were thus assigned the highest score of 3. The **meteorological stations**
 580 **(precip.isotope/amount)** data sourced from meteorological stations, while still based on measurements, are deemed less
 581 directly representative of site-specific conditions and were scored 2. In cases where neither local nor station-based input were
 582 available, the input data from **Global products** were provided as substitutes and assigned a score of 1. The total grade for each
 583 spring and cave site was calculated from the sum of its output and input data scores, based on the assessment criteria stated
 584 above. The sites evaluation was then divided into three classes that reflect the overall reliability and completeness of the data
 585 collection.

- 586 • **Class I** (scores from 10 to 12): indicating robust datasets with high quality, generally obtained from raw output origins
 587 and/or locally measured inputs. The site in this category keeps the most complete and reliable datasets, providing
 588 comprehensive information for interpretation and modelling of karst systems.
- 589 • **Class II** (scores from 7 to 9): reflecting the datasets with moderate quality that might have less site-specific input
 590 sources or digitized outputs. Although less strong, these data are still valuable for studies in both karst geohydrology
 591 and speleology.
- 592 • **Class III** (scores below 7): the sites with lower-confidence data, primarily relying on digitized records or global
 593 modelled data. These datasets are helpful in identifying data-scarce regions and highlighting the need for more data
 594 collection.

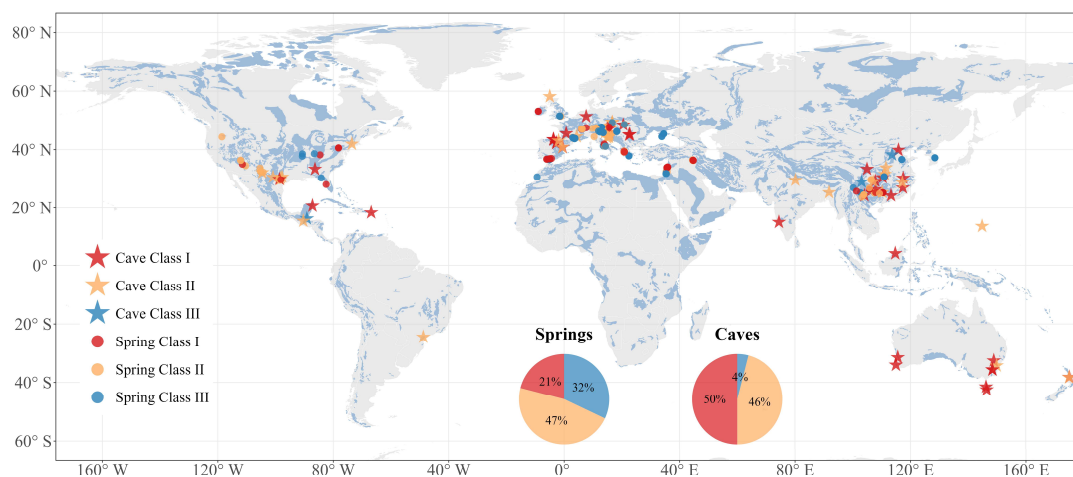
Table 6: The grading system for evaluation of the WoKaS-Iso database for karst springs and caves. *Example:* a spring with collected spring discharge (3 points), collected spring isotopes (3 points), local observation of precipitation isotopes (3 points), and local precipitation amount (3 points) receives a total score of 12. *Note:* the “No data” category is assigned to sites without flow rate data or aligned with SISAL_mon_v1 database at Shenqi Cave, as no cave drip water data are available and only input data are provided.

System output data		System input data	
Variable	Assigned Score	Variable	Assigned Score
Collected spring discharge/drip rate	3	Local observation (precip. isotope/amount)	3
Collected spring /drip water isotope			
Digitized spring discharge/drip rate	2	Meteorological stations (precip.isotope/amount)	2
Digitized spring/drip water isotope			
No data	0	Global products	1



595

596 Attributing the quality classes to all our sites shows that most of them fall within Class I and Class II (Figure 8). For springs,
597 21% are categorized into Class I, and are predominantly distributed in China, Europe and the Middle East. Class II springs,
598 the most common category, occupied 47%, due to scarcity and limited availability of locally measured rainfall and rainwater
599 isotopes for karst springs; while Class III accounts for 32%, with a high proportion due to the absence of paired precipitation
600 and precipitation isotopes measurements for karst springs, the substitute modelled data were used. Class I and Class II are
601 spread relatively evenly globally, while Class III springs are primarily found in Europe where karst spring monitoring is more
602 extensive in the WoKaS-Iso database. For cave sites, a high proportion of 50% is classified as Class I, Class II reached 46%,
603 with only a small proportion of 4% falling into Class III. The distribution characteristics reflect the more complete and robust
604 monitoring systems available for caves compared to karst springs. The Class I cave sites are mainly suited in Australia, China
605 and Europe. The Class II caves are mostly located in Europe and the USA. Only 4 caves are grouped as Class III, scattered
606 over various regions.
607



608

609 **Figure 8:** Spatial distribution of karst springs and cave sites in the WoKaS_Iso database according to data quality evaluation classes. Blue
610 areas indicate karst regions as delineated in the World Karst Aquifer Map (WOKAM, Chen et al., 2017). Star symbols refer to caves and
611 circle symbols represent springs. Colours represent the three quality tiers: Class I (red), Class II (orange), and Class III (blue). Accompanying
612 pie charts illustrate the proportion of each quality class for springs and caves, respectively.



613 **5 Data availability**

614 The dataset is available in the public repository at: <https://doi.org/10.25532/OPARA-909> (Zang, 2025).

615 **6 Recommended usage and outlook**

616 The data quality classification provides guidance for users on the proper application and interpretation of each site. **Class I**
617 with the most complete observational records are recommended for process-based model calibration and validation,
618 characterization of the karst system and paleoclimate construction. **Class II** consisting of partial measurements or digitized
619 output data or station-based input data/ modelled sources are appropriate for regional-scale comparative studies, trend analysis
620 and model sensitivity testing. Although less precise than Class I, these datasets remain valuable in regions with limited
621 monitoring. **Class III**, which rely highly on digitised outputs and global products inputs, are useful for global exploratory
622 studies, particularly in data-scarce regions. Global products offer critical alternatives where observations are unavailable and
623 support long-term climate analysis. Based on our analysis, we recommend **IsoGSM** as the preferred substitute of precipitation
624 isotope input. Future development of WoKaS-Iso efforts will focus on expanded spatial coverage and improving data quality
625 through encouraging the sharing of raw data from literatures, reports, internal databases and unpublished records by researchers,
626 institutions and monitoring programs, especially in underrepresented regions such as Africa, South America and Southeast
627 Asia. Enhancements will include more detailed metadata, uncertainty estimates, data quality flags to improve usability. A web-
628 based interface with visualizations is planned to assist data access.

629 **7 Author contributions**

630 YZ and AH collected the karst spring datasets. PCT and YZ contacted data contributors to obtain cave drip water data and
631 aligned this dataset with the SISAL_mon_v1 dataset. YZ designed the structure of WoKaS-Iso database and organized the
632 datasets. YZ digitized data from publication figures. YZ, AH, JGP and FZ contributed to data quality control. KY extracted
633 IsoGSM datasets for each site and YZ performed data extraction from other global products. YZ developed extraction scripts
634 for MSWEP, GLEAM and ERA5, with KOC and XM assisting in code testing. YZ drafted the manuscript under the
635 supervision of AH. All other authors contributed data to the WoKaS-Iso database.

636 **8 Competing interests**

637 The authors declare that they have no conflict of interest.



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