

# Decoding multicomponent hydrochemical anomalies: A synergy anomaly detection model for earthquake forecasting in active tectonic zone

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**Abstract.** The intersection of the Xiaojiang Fault and the Red River Fault at the southeastern margin of the Tibetan Plateau ~~experiences-encounters~~ intense tectonic activity. At this intersection, ~~frequent-repeated~~ destructive earthquakes have ~~induced-led~~ to variations in the hydrochemistry of the ~~hydrochemical-variations-in~~ thermal springs. ~~In-This study applies,~~ Bayesian change point analysis and develops a multi-component synergy anomaly detection model using five years of monitoring data (2019–2024) from two thermal springs in this region to facilitate the real-time forecasting of the occurrence timing for ~~is applied, and a multicomponent synergy anomaly detection model is developed using five years of monitoring data (2019–2024) from two thermal springs in the region to achieve real time forecasting of occurrence timing for~~  $M \geq 4$  earthquakes. ~~Comprehensive analysis demonstrates that the anomaly detection model possesses reliable real time anomaly detection capabilities. Tailored model parameters for specific hydrochemical components account for their differences in response characteristics to seismic activity. The model identifies  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\delta\text{D}$ , and  $\delta^{18}\text{O}$  as sensitive indicators for strong earthquake forecasting.~~ A 45-day response time threshold is established as the optimal period for capturing critical hydrochemical precursors associated with  $M \geq 4$  earthquakes. Parameters are optimised for individual components based on their distinct geochemical responses to seismic stress, thereby substantially refining the model's performance and adaptability. The model exhibits reliable real-time detection capabilities, with the probability of detection (POD) ranging from 0.83 to 0.95 and threat score (TS) between 0.59 and 0.70. It identified pre-earthquake anomalies in  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\delta\text{D}$ , and  $\delta^{18}\text{O}$ , with  $\text{TS} \geq 0.50$ , which can serve as sensitive indicators for strong earthquake

forecasting. The multicomponent synergy alarm mechanism for hydrochemistry overcomes the limitations of single-parameter methods, significantly boosting ~~which significantly enhances~~ the model's overall performance in earthquake forecasting. The number of hydrochemical components with synchronous anomalies serves as a reliable criterion for determining alarm intensity, with higher intensity typically correlating with larger earthquake magnitudes or shorter epicentral distances. This model can be universally applied to thermal spring monitoring across diverse tectonic regions through targeted parameter optimisation, offering a valuable reference for earthquake forecasting.

## 1. Introduction

Earthquake forecasting, a frontier in geosciences, relies on detecting sensitive and reliable precursor anomalies (Chen, 2009; Pritchard et al., 2020). Although several geophysical methods (e.g., seismology, geomagnetism) are extensively employed in this field (An et al., 2019; Chen and Zhu, 2020; Nayak et al., 2024), hydrochemical methods that monitor subsurface fluids exhibit unique advantages for short-term and imminent forecasting (Li et al., 2023). Because of ~~Subsurface fluids, owing to~~ their ease of migration and incompressibility, subsurface fluids respond rapidly to deviations in dynamic crustal stress ~~changes~~ during earthquake preparation. These responses often induce considerable variations ~~result in significant changes~~ in the physiochemical ~~physical and chemical~~ properties of the fluids, such as their ion concentrations and isotopic ratios (Lee et al., 2017; Gori and Barberio, 2022; Tian et al., 2023; Skelton et al., 2024). Moreover, subsurface fluids can transmit deep geological signals to the surface, ~~for example, through~~ via thermal springs, making ~~which makes~~ them valuable targets for monitoring precursor anomalies. Currently, earthquake-related anomalies in subsurface fluids are ~~prevalently observed widely monitored~~ across numerous ~~various~~ spatial and temporal scales. These include hydrological anomalies such as water temperature, water level, and flow rate (Shi et al., 2015; Lee et al., 2017; Petitta et al., 2018; Di Matteo et al., 2020; Du et al., 2023), hydrogeochemical anomalies ~~such as like~~ major elements, trace elements, and stable isotopes (Ide et al., 2020; Nakagawa et al., 2020; Barbieri et al., 2021; Wang et al., 2021; Zhang et al., 2021; Yan et al., 2022), and gas geochemical anomalies such as radon, helium, and carbon dioxide (Chaudhuri et al., 2011; Fu et al., 2017; Woith et al., 2020; Zhao et al., 2021; Zhou et al., 2021). Although ~~While~~ some fluid precursor anomalies have ~~displayed shown~~ predictive value, many are still identified only ~~via through~~ retrospective analysis after earthquakes. Moreover, continuous fluid monitoring data often reflect integrated signals from multiple sources, including seismic activity, environmental variability, and human-induced influences (Martinelli, 2020). The isolation of true seismic precursor anomalies from such ~~intricate complex~~ datasets remains a ~~gigantic significant~~ challenge in current earthquake

forecasting research.

In the analyses of large-scale fluid monitoring data, traditional anomaly detection methods typically ~~depend~~ ~~rely~~ on manually defined fixed thresholds to identify fluctuations. Techniques such as trend analysis and standard deviation methods offer clear advantages in capturing prominent anomalies (Ingebritsen and Manga, 2014; Yan et al., 2018). However, in practice, fluid monitoring data often integrate superimposed signals from both tectonic and non-tectonic sources and ~~display convoluted~~ ~~exhibit complex~~ nonlinear dynamic behaviors. These characteristics ~~exhibit~~ ~~present~~ notable limitations for ~~conventional~~ ~~traditional~~ statistical approaches in effectively ~~determining~~ ~~identifying~~ fluid precursor anomalies (Yan et al., 2021). Machine learning-based anomaly detection algorithms ~~provide novel insights for earthquake forecasting by~~ ~~revealing hidden precursor signals within vast~~ ~~offer new perspectives for earthquake forecasting by uncovering hidden~~ ~~precursor signals within large~~ volumes of monitoring data (Li et al., 2022, 2023). In recent years, algorithms such as artificial neural networks, long short-term memory networks, and random forests have been ~~widely~~ ~~mostly~~ applied to anomaly detection in individual indicators, such as water levels and radon concentrations, ~~markedly~~ ~~significantly~~ enhancing detection accuracy and sensitivity (Tareen et al., 2019; Haider et al., 2021; Feng et al., 2022; Zhang et al., 2025). However, single-indicator measurements are easily ~~affected~~ ~~influenced~~ by meteorological, tidal, and other environmental factors. ~~Although~~ ~~While~~ regression models and similar techniques have been used to correct these interferences, challenges remain in effectively distinguishing non-seismic anomalies (Woith, 2015; Soldati et al., 2020). Moreover, single-indicator analysis does not leverage the synergistic relationships among multiple indicators, ~~which~~ ~~thus~~ ~~restricting~~ ~~limits~~ its ability to ~~improve~~ ~~enhance~~ the reliability of anomaly identification.

Thermal springs are natural discharge outlets ~~for deep-circulating groundwater, offering of deep-circulating groundwater~~ ~~and they offer~~ distinct advantages for hydrogeochemical monitoring. ~~The hydrochemical components (e.g., Na<sup>+</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>) of thermal springs tend to exhibit high stability, rapid upward migration, and limited susceptibility to environmental interference~~ The hydrochemical components (e.g., Na<sup>+</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>) of thermal springs tend to exhibit greater stability against short-term environmental fluctuations (e.g., temperature, short-term rainfall) than near-surface cold water systems, alongside deep circulation depth, rapid upward migration and limited susceptibility to anthropogenic influence (Luo et al., 2023; Yakupoğlu et al., 2025). These ~~characteristics help minimise non-seismic noise and allow for~~ features help minimise non-seismic noise and enable a more accurate reflection of hydrogeological changes during earthquake preparation (Martinelli, 2020; Tian et al., 2024). Numerous studies have reported diverse geochemical behaviors among hydrochemical components, which ~~shows marked~~ ~~depict~~ ~~notable~~ differences in their response magnitude, quantity, patterns, and timing to

tectonic stress variations throughout the earthquake preparation process (Li et al., 2021; Yan et al., 2022; Tian et al., 2023).

Therefore, applying anomaly detection algorithms to evaluate the abnormal response characteristics of individual hydrochemical components and integrating multiple components to ~~raise the~~ ~~enhance~~ anomaly identification accuracy may represent a promising technical approach for precursor recognition. Current research on hydrochemical anomaly detection algorithms remains in an exploratory stage (Castellana and Biagi, 2008). Existing studies have demonstrated the effectiveness of ~~common machine learning algorithms~~ widely implemented machine learning algorithms (e.g., Isolation Forest, Local Outlier Factor, and Autoencoder) in ~~detecting~~ ~~identifying~~ abnormal periods in hydrochemical data while also emphasising the need for scenario-specific optimisation of ~~crucial~~ ~~key~~ indicators (Zhu et al., 2024). However, there is an urgent need to investigate the synergistic anomaly response patterns among hydrochemical components and to identify sensitive indicators for reliable forecasting of strong earthquakes.

This study focuses on the tectonically active region at the intersection of the Xiaojiang Fault (XJF) and the Red River Fault (RRF) on the southeastern margin of the Tibetan Plateau. ~~The real-time anomaly was innovatively modified using the detection algorithm developed by Piersanti et al. (2016), and its application was extended to the analysis of multiple hydrochemical components in thermal springs across the study area.~~ The anomaly detection algorithm originally developed by Piersanti et al. (2016) for radon time series was adapted for real-time multicomponent hydrochemical analysis in thermal springs within the study region. By integrating the continuous monitoring data of hydrochemical ions and hydrogen-oxygen isotopes with earthquake catalogues and applying Bayesian change point (BCP) analysis, this study optimised parameters for specific components and ~~created~~ ~~built~~ a multi-component joint anomaly detection model. This model supports anomaly detection in both long-term time series and real-time earthquake forecasting across different time scales.

The ~~primary~~ ~~main~~ objectives of this study are summarised as follows: (1) to evaluate the applicability and performance of the algorithm in analysing hydrochemical time series; (2) to ~~determine~~ ~~identify~~ effective hydrochemical indicators for forecasting strong earthquakes in the study area; and (3) to assess the feasibility of the multi-component joint anomaly detection model and explore the relationship between hydrochemical variations and seismic activity by ~~analysing~~ ~~examining~~ the number of components with synchronous anomalies.

## 2. Geological setting

The southeastern Tibetan Plateau ~~underwent~~ ~~has undergone~~ sustained rotation and southeastward extrusion, driven by the collision-induced uplift and deformation between the Indian and Eurasian plates. The rotation and extrusion effects have

115 resulted in the formation of an active tectonic region characterised by large-scale strike-slip fault systems and the presence of intracontinental microplates (Tapponnier et al., 1982; Yin and Harrison, 2000; Xu et al., 2011) (Figure 1). Among these structures, the XJF and RRF serve as essential key-strike-slip boundaries, playing and play critical roles in the tectonic evolution and material extrusion of the southeastern Tibetan Plateau (Zhang et al., 2003; Tong et al., 2015). The intersection area of the XJF and RRF serves as the frontal zone accommodating the extrusion of the Sichuan–Yunnan Block (SYB). The XJF is blocked by the Indochina Block (ICB) and has not yet propagated southward through the RRF, which makes the intersection area the primary zone of stress accumulation, where there is an ongoing dextral compressional motion of the SYB-occurs (Wen et al., 2022; Li et al., 2024; Shao et al., 2024). The deeply incised XJF and RRF, along with secondary faults such as the Qujiang Fault (QJF) and Shiping–Jianshui Fault (SJF) in this region, act as conduits for deep-circulating thermal waters and the exchange of seismic information, with thermal springs commonly observed found along these faults. This area experiences prolonged stress accumulation and intense tectonic deformation, accompanied by historical moderate -to -strong seismic activity (Wen et al., 2008), -which makes making it a critical zone for earthquake hazard monitoring. 125 Consequently, this region is an ideal setting for investigating how variations in hydrochemical compositions respond to seismic activity.

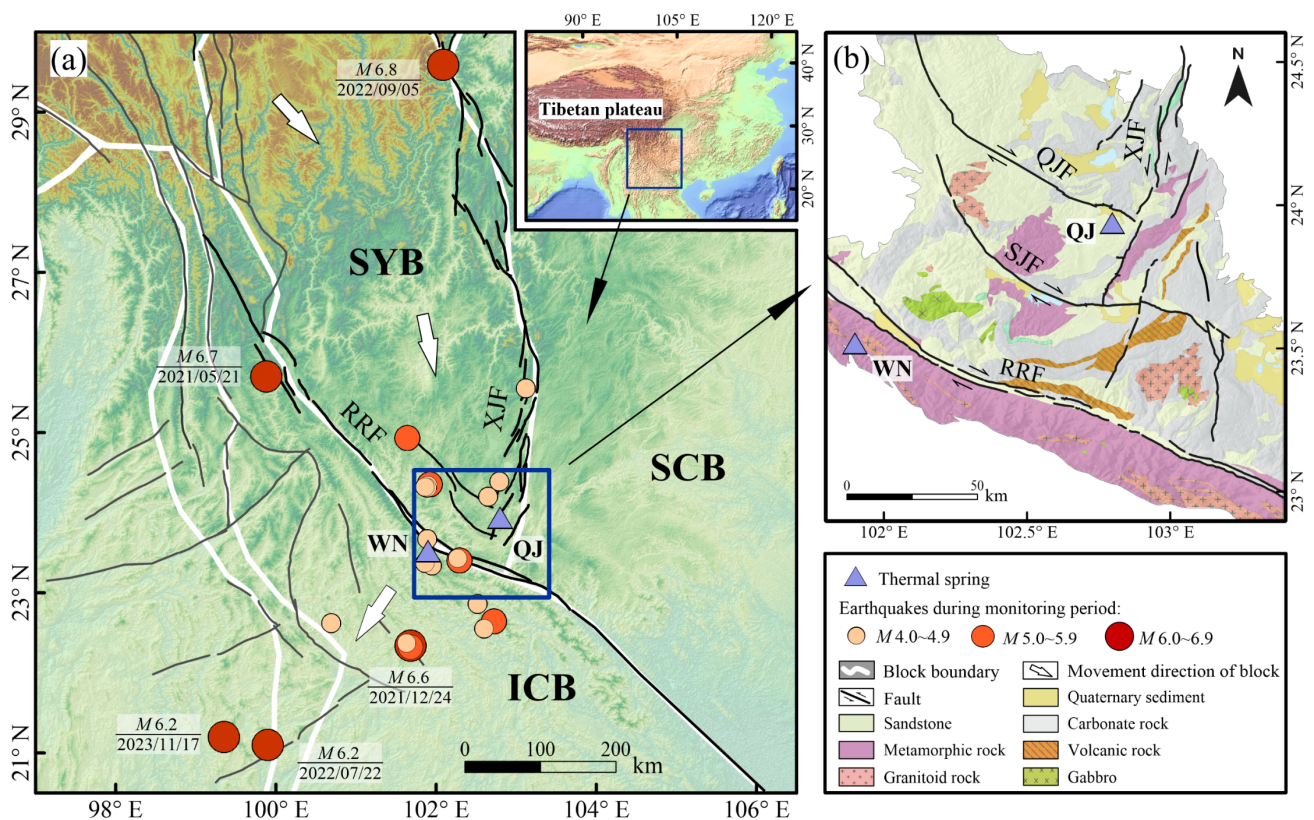


Figure 1: (a) Simplified tectonic map of the southeastern margin of the Tibetan Plateau, presenting showing the distribution of  $M \geq 4$  earthquakes during the thermal spring monitoring period. (b) Locations of continuously monitored thermal spring sites,

130 fault distribution, and the geological map at the intersection of the Xiaojiang Fault (XJF) and Red River Fault (RRF). Earthquake catalogues are obtained from the China National Earthquake Data Center (<https://data.earthquake.cn/>). The tectonic divisions and active faults are sourced from Deng et al., (2002), and the geological map is adapted from Ma et al., (2002). SYB: Sichuan–Yunnan Block; ICB: Indochina Block; SCB: South China Block; QJF: Qujiang Fault; SJF: Shiping–Jianshui Fault.

135 This study employs ~~involves~~ continuous hydrochemical monitoring at two high-temperature springs, namely Qujiang (QJ) and Wana (WN), located at ~~crucial key~~ tectonic sites within the research area (Figure 1b). QJ is situated at the intersection of the XJF and the QJF, with sandstone as the predominant country rock. QJ is positioned at a critical location where the sinistral slip rate of the XJF decreases sharply from 8–11 mm/a to approximately 4 mm/a after crossing the QJF (Wen et al., 2011; Wang et al., 2014). WN, located along the RRF, is hosted by gneiss and mylonite and lies within a stress concentration zone, where the SYB ~~experiences undergoes~~ southwestward deflection, compressing the RRF (Schoenbohm et al., 2006; Li et al., 2019; Wen et al., 2022). The two hot springs are ~~situated along the boundary faults that regulate the regional tectonic pattern, and their hydrochemical variations may serve as located along the boundary faults that control the regional tectonic pattern, and their hydrochemical variations may provide~~ sensitive indicators of changes in the earthquake preparation state within the intersection area.

### 145 3. Data and methods

#### 3.1. Thermal spring monitoring data

The monitoring period for the QJ spring spanned from 1 June ~~1~~, 2019, to 21 May ~~21~~, 2024 (approximately 5 years), while the WN spring was monitored from 3 October ~~3~~, 2021, to 21 May ~~21~~, 2024 (approximately 2.5 years). A ~~s~~Synchronous monitoring of hydrogen and oxygen isotopes was conducted at both springs between 1 ~~1~~–January ~~1~~, 2023, and 21 February ~~21~~, 2024. ~~All monitoring parameters for the thermal springs and their hydrochemical components were measured every three days. Water temperature, pH, and electrical conductivity (EC) were measured in situ using a portable multi-parameter water quality analyser (HQ40D, HACH, USA), with measurement accuracies of 0.1°C, 0.01, and 1 µS/cm, respectively. Water temperature, pH, electrical conductivity (EC) and hydrochemical components for the thermal springs were measured every three days. Rainfall data were collected through continuous in situ monitoring using an RTP-II tri-element meteorological instrument with a resolution of 0.1 mm. Before collecting the thermal water samples, high-density polyethene (HDPE) bottles were thoroughly rinsed thrice with deionised water and twice with the the thermal water samples~~

160 were collected, high density polyethylene (HDPE) bottles were thoroughly rinsed three times with deionised water and twice with thermal water. Water samples were then filtered through 0.45 µm micropore membranes and stored in HDPE bottles. Samples intended for cation analysis were acidified with high-purity nitric acid. During collection, care was taken to prevent the introduction of air bubbles, and the samples were immediately sealed hermetically to preserve them for preservation.

165 The concentrations of major ions (Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, Li<sup>+</sup>, F<sup>-</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, Br<sup>-</sup>, NO<sub>3</sub><sup>-</sup>) were analysed using a Thermo Scientific Dionex Aquion IC system equipped with an AS40 autosampler, which had a detection limit of 0.01 mg/L. HCO<sub>3</sub><sup>-</sup> and CO<sub>3</sub><sup>2-</sup> concentrations were determined via standard titration procedures using a ZDJ-3D potentiometric titrator with 0.05 mol/L HCl. δ<sup>18</sup>O and δ<sup>2</sup>H values were determined using a Picarro L2140-i water isotope analyser, with precisions of 0.015 ‰ and 0.05 ‰, respectively. All analyses were conducted at the Key Laboratory of the Institute of Earthquake Forecasting, China Earthquake Administration. The monitoring data are detailed in data set S1. To ensure data accuracy, cation-anion balance error tests were performed for each sample as a quality control measure, with all ionic deviations kept within ± 5 %. Data that fulfilled this criterion were included in the subsequent analysis. The ion balance error (Appelo and Postma, 2004) is calculated as below:

$$ib(\%) = \frac{\sum cations - \sum anions}{\sum cations + \sum anions} \times 100 \quad (1)$$

170 where  $\sum cations$  represents the sum of cation concentrations (in milliequivalents per liter, meq/L), and  $\sum anions$  represents the sum of anion concentrations.

### 3.2. Earthquake data collection and processing

175 The anomaly detection model developed in this study aimed to forecast earthquakes with  $M \geq 4$  by determining pre-earthquake anomalous signals focused on forecasting destructive earthquakes with magnitudes ( $M$ )  $\geq 4$ . To identify earthquakes that might affect influence hydrochemical component variations, while excluding those unrelated to precursors, and to establish a precise correlation between variations changes in hydrochemical components and seismic activity, an earthquake screening method based on the preparation of a zone radius formula (Dobrovolsky et al., 1979) was employed:

$$R = 10^{0.43M} \quad (2)$$

180 where  $M$  represents the earthquake magnitude, and  $R$  denotes the radius (in km) of the earthquake preparation zone. Based on long-term observations of 27 radon-involved earthquake cases in China between 1997 and 2020, 9 widely applied prediction methods were evaluated. The findings demonstrated that Dobrovolsky's formula achieved the highest

applicability rate, reaching 96.30 % (Li et al., 2023). Its practical utility is further confirmed by recent studies in complex tectonic settings (Yakupoğlu et al., 2025), establishing it as an empirically robust and widely adopted reference scale for selecting potentially correlated earthquake events (Li et al., 2023; Seminsky and Seminsky, 2024; Zhu et al., 2024).

Earthquakes were selected as study events based on the criterion that the epicentral distance ( $\Delta$ ) from the thermal spring monitoring sites did not exceed the earthquake preparation zone radius ( $R$ ) (Figure 1a). The QJ site was within the preparation zones of 22 earthquakes with  $M \geq 4$  earthquakes during its monitoring period (1 June 2019/06/01–21 May 2024/05/21), whereas while the WN site was within the preparation zones of 12 earthquakes with  $M \geq 4$  earthquakes during its observation period (3 October 2021/10/03–21 May 2024/05/21) (Table S1). All earthquakes had focal depths ranging from 8 to 16 km, and were classified as they were classified as shallow-focus events. The earthquake catalogue was obtained from the National Earthquake Data Center of China (<http://data.earthquake.cn>).

Seismic moment ( $M_0$ ), which directly reflects fault geometry parameters and the rigidity of the surrounding medium, accurately quantifies earthquake rupture processes and the mechanical energy released during the event. medium, accurately quantifies earthquake rupture processes and mechanical energy release. Compared with magnitude scales, the seismic moment is more suitable for analysing the seismic impact on hydrochemical component changes in thermal springs. The commonly used empirical formula for estimating seismic moment based on magnitude (Hanks and Kanamori, 1979) is expressed as follows:

$$\lg M_0 = 1.5M + 16.1 \quad (3)$$

Stress attenuates with increasing epicentral distance during the earthquake preparation process-, directly influencing and directly influences the development of thermal water seepage pathways and the intensity of water-rock interactions (Wang and Manga, 2010; Ingebritsen and Manga, 2019). To account for distance-related effects, the seismic moment requires correction using the following empirical formula (Piersanti et al., 2016):

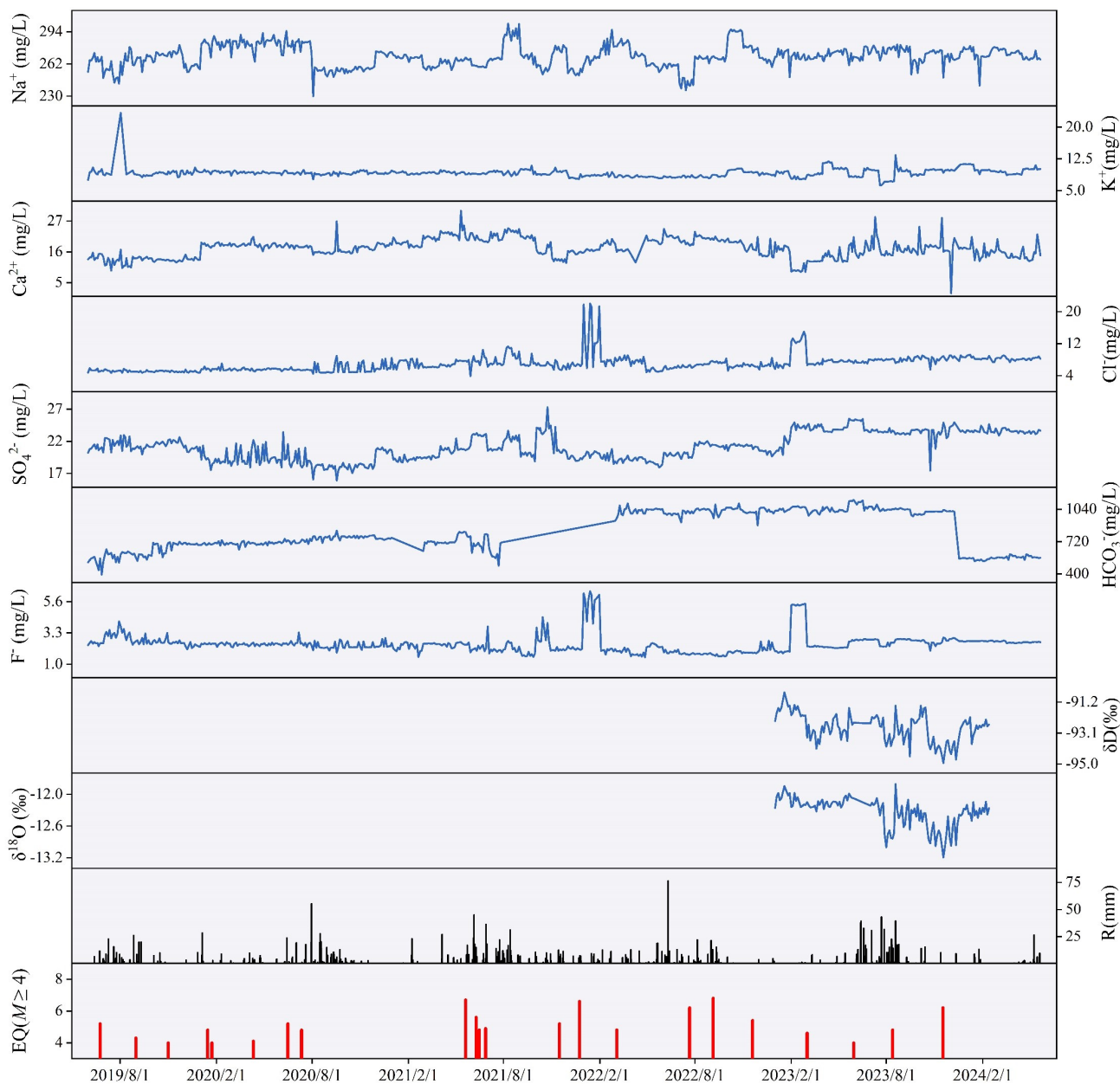
$$M_{0cor} = M_0 / \Delta^\omega \quad (4)$$

where  $\omega$  is the weighting factor., in this study  $\omega$  takes the value of 1. A sensitivity analysis was performed by testing multiple values of  $\omega$  (including 0, 0.5, 1, 1.5, 2, 2.5, and 3). It was observed that the cross-correlations peak (the methodology for which is presented in Section 3.3.2) consistently emerged within the same lag range across all  $\omega$  values. Among these, the cross-correlations for  $\omega = 0, 0.5, \text{ and } 1$  were relatively significant and exhibited minimal differences (Figure S1).

Considering the physical interpretability, in this study,  $\omega$  takes the value of 1.

### 3.3. Hydrochemical component time series

215 The geochemical behaviours of different components in thermal spring water exhibit significant variations, with each element displaying behaviors of different components in thermal spring water show significant variation, with each component exhibiting distinct characteristics with respect to in terms of anomaly amplitude, temporal evolution, and precursor response sensitivity. Regulated Controlled by unique hydrogeological conditions, the hydrochemical variations of each thermal spring also display spatial differences in response to tectonic activity. To effectively extract anomalous signals, the anomaly responses of different components and springs in the study area are compared, and the algorithm's generalisability across springs is validated. This study establishes independent time series for each component at different springs (Figure 2 and S42).



**Figure 2: Time series of hydrochemical components at Qujiang spring, along with rainfall and earthquake events. Time series of hydrochemical components ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{F}^-$ ,  $\delta\text{D}$ , and  $\delta^{18}\text{O}$ ), alongside corresponding rainfall and earthquake events for Qujiang spring.**

### 3.3.1. Data evaluation and noise removal

225 The dynamic variations in thermal spring ion concentrations are crucial for identifying seismic precursors. When observed data show minimal fluctuations or remain consistently below detection limits over extended periods, it becomes challenging to effectively extract hydrogeochemical anomaly signals before an earthquake. Long-term monitoring reveals that concentrations of  $\text{Mg}^{2+}$ ,  $\text{Br}^-$ , and  $\text{NO}_3^-$  are extremely low and remain consistently below instrumental detection limits, without temporal fluctuations, which thus limits their value for tracking seismic precursors. Consequently,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,

230  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{F}^-$ ,  $\delta\text{D}$ , and  $\delta^{18}\text{O}$  have been selected for earthquake anomaly identification ~~owing due~~ to their consistent continuity and reliable data characteristics.

The thermal spring water in the study area originates from atmospheric precipitation recharge. It circulates deeply through faults, is heated by geothermal energy, and then discharges at the surface, with its hydrochemical composition ~~primarily mainly~~ determined by the lithology of the surrounding rocks (Shao et al., 2024). Consequently, ambient temperature and atmospheric pressure at the spring outlet ~~exert have~~ a negligible effect on the hydrochemistry. However, rainfall serves not only as the primary water source but also accelerates groundwater circulation, ~~fosters promotes~~ shallow infiltration, and mixes with thermal waters (Taylor et al., 2012; Hosono et al., 2020; Colman et al., 2021). This process can potentially obscure deep-seated earthquake preparatory signals carried by the thermal spring. Consequently, this study focuses on assessing the potential perturbations induced by rainfall on thermal spring hydrochemistry. ~~The comparative analysis of hydrochemical and meteorological data (Figure S3) reveals that rainfall is the dominant interfering factor, accompanied by a partial decrease in ion concentrations following events, In contrast, the effects of temperature and pressure are negligible.~~ Unlike temperature and pressure, rainfall causes pulsed disturbances, typically manifesting as intermittent spikes followed by extended ~~periods of zero values zero-value intervals in rainfall sampling~~ data. Previous studies usually employ a 14-day moving average to filter out such interference, a method that has been established as effective in geochemical analysis (Piersanti et al., 2016; Fu et al., 2017; Zhao et al., 2021). To suppress high-frequency noise from short-term environmental disturbances such as rainfall while preserving mid- to low-frequency tectonic signals, a 15-day backward moving average is applied to process the 3-day resolution hydrochemistry data:

$$MA(t) = \frac{1}{15} \sum_{t-14}^t Dr(t) \quad (5)$$

where  $MA$  is the 15-day moving average, and  $Dr$  is the daily raw data.

### 250 3.3.2. Correlation analysis

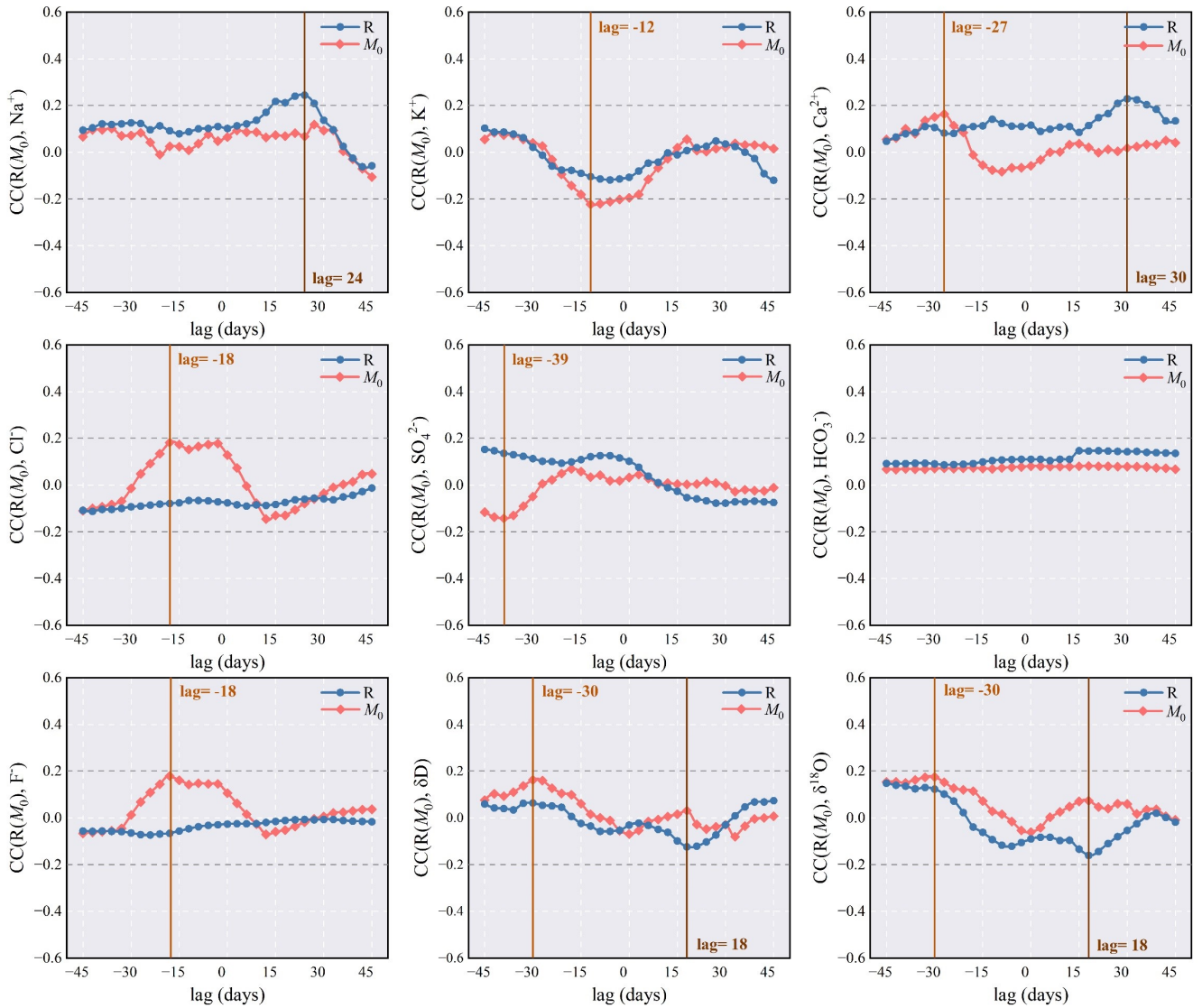
The influence of rainfall on the hydrochemical dynamics of thermal springs may exhibit a lag effect, while hydrochemical precursor anomalies induced during earthquake preparation processes typically precede earthquake events. These two mechanisms exhibit a significant temporal phase difference in their perturbations to hydrochemical components. In this study, the cross-correlation function is ~~applied employed~~ to quantitatively analyse the temporal offset between the impacts of rainfall and seismic activity on thermal spring hydrochemistry. This study aims to identify the maximum correlation

time offset between rainfall-hydrochemistry and precursory anomaly-main shock events by calculating ~~via the calculation~~ of correlation coefficients at varying lag times. The cross-correlation function (Chatfield, 1975; Brockwell and Davis, 1991) is ~~represented defined~~ as follows:

$$CC_{xy}(k) = \frac{1}{N} \sum_{t=1}^{N-k} (x_t - \bar{x})(y_{t+k} - \bar{y}) \quad (6)$$

260 where  $x$  and  $y$  are two time series,  $\bar{x}$  and  $\bar{y}$  represent their sample means,  $N$  is the series length, and  $k$  denotes the lag. Considering the seasonal effects of rainfall and ~~the reliability of seismic precursor response times, the response time reliability of seismic precursors, the~~  $k$  is set within a range of  $-45$  to  $45$  days.

In the cross-correlation analysis, the denoised hydrochemical component time series (processed using a 15-day moving average) are correlated with both the rainfall time series and the distance-corrected  $M_0$  time series. This analysis aims to  
265 evaluate the effectiveness of the moving -average method in filtering out rainfall-induced interference by assessing the correlation intensity between the denoised hydrochemical time series and rainfall. ~~Meanwhile At the same time~~, the analysis verifies ~~the~~ potential temporal linkages between the denoised hydrochemical components and regional seismic moment release.



270 **Figure 3: Cross-correlation function analysis of the 15-day moving average time series of hydrochemical components during stable isotope monitoring, with rainfall and distance-corrected seismic moment.**

The results of the cross-correlation analysis (Figure 3) show weak correlations (blue dotted lines) between rainfall events and the 15-day moving average hydrochemical component time series, with correlation coefficients approximately within  $\pm 0.2$ . This result indicates that the moving average treatment effectively mitigates rainfall induced noise. Notably,  $\text{Na}^+$ ,

275  $\text{Ca}^{2+}$ ,  $\delta\text{D}$ , and  $\delta^{18}\text{O}$  exhibit minor response peaks at lags of 18–30 days, suggesting that certain impacts on these components persist 15 to 30 days after rainfall. Similarly, the correlations between the distance-corrected  $M_0$  and the denoised hydrochemical component time series (red dotted lines) remain low (around  $\pm 0.2$ ). However,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{F}^-$ ,  $\delta\text{D}$ , and  $\delta^{18}\text{O}$  exhibit weak response peaks at lags of -39 to -12 days, with varying peak directions for each component. This observation suggests that seismic activity (12–39 days before seismic moment release) may influence hydrochemical components, causing their concentrations to fluctuate (either increasing, decreasing, or remaining stable) owing to different

280

~~geochemical mechanisms.~~

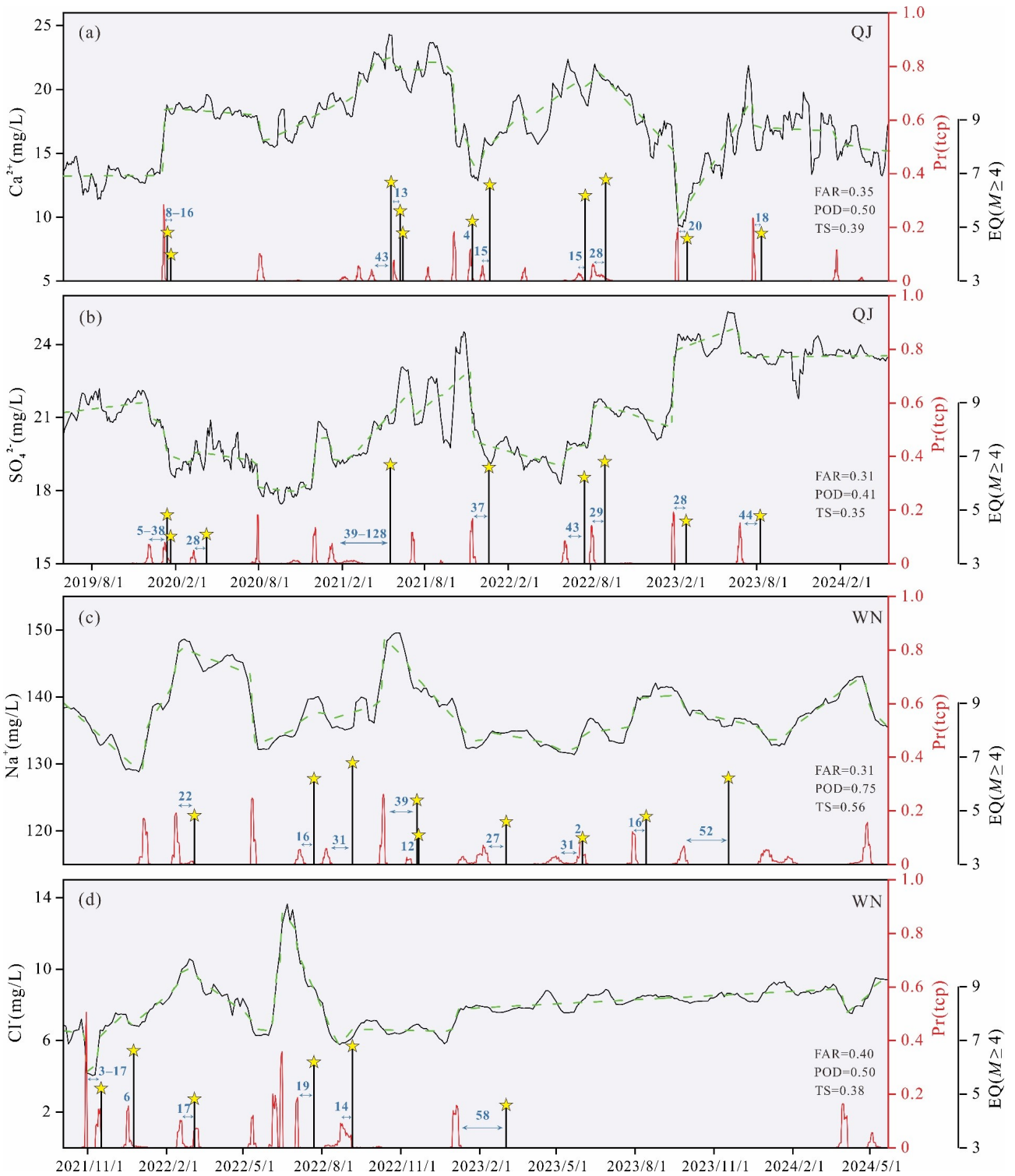
### 3.4. Detection algorithms

#### 3.4.1. BCP analysis

285 ~~The correlation analysis results indicate that changes in environmental parameters have little to no significant influence on denoised hydrochemical components, or their effects were slow processes. Consequently, these component time series appear to follow specific distribution patterns.~~ Assuming that the denoised hydrochemical component time series appear to adhere to specific distribution patterns. However, since earthquake events are stochastic and hydrochemical anomalies (i.e., change points) emerge during the pre-earthquake period without a known rupture time, continuous hydrochemical monitoring data exhibit non-stationary variations. Therefore, the BCP analysis is applied to effectively extract anomalous  
290 signals from these component time series, and determine the timing of their appearance, thereby verifying their correspondence with earthquakes for earthquake forecasting.

~~To detect change points in pre-seismic hydrochemical component time series and verify their correspondence with earthquakes for forecasting future earthquake occurrences, the BCP analysis algorithm, which is developed for Earth climate systems (Ruggieri, 2012) to the 15-day moving average time series of all component concentrations from QJ and  
295 WN, is applied to this study.~~

The BCP algorithm, initially developed for Earth's climate systems (Ruggieri, 2012), is applied here to the 15-day moving average time series of all hydrochemical component concentrations from QJ and WN. The analysis produces Bayesian predictive model curves, change point locations, and posterior probabilities for each component. The posterior probabilities represent the likelihood of change point occurrences in the predictive models, with probability peaks ~~implying indicating~~  
300 the most likely timings of change points.



**Figure 4: Anomaly detection results from the Bayesian change point (BCP) analysis applied to hydrochemical component time series. The black solid line represents the component concentration after 15-day moving averaging. The green dashed line indicates the forecasting model of the BCP algorithm. The red solid line shows the posterior probability of change points. Yellow stars mark earthquake events. The false alarm rate (FAR), probability of detection (POD), and threat score (TS) are evaluation metrics; further details are provided later.**

The results show that change points are successfully detected in all component time series from both thermal springs

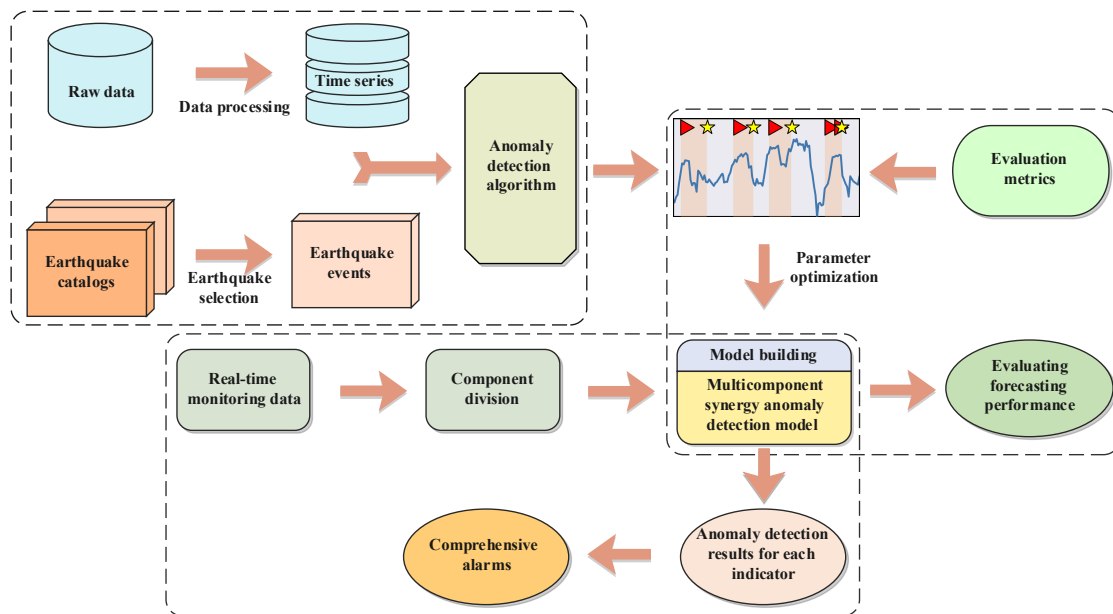
(Figure 4). For example, before the  $M6.6$  earthquake on December 24, 2021, the posterior probability for a  $\text{Ca}^{2+}$  change point at QJ was 0.06 at 15 days before the earthquake, while  $\text{SO}_4^{2-}$  exhibited a posterior probability of 0.17 at 37 days before the earthquake. Similarly, before the  $M5.2$  earthquake on November 16, 2021,  $\text{Cl}^-$  at WN showed posterior probabilities for change points of 0.15 and 0.51 at 3 and 17 days before the earthquake, respectively. Notably, the timing and posterior probabilities of change points exhibit significant uncertainty, which reflects the complexity of factors influencing hydrochemical component variations. These factors include inhomogeneity in stress accumulation, the structural complexity of fault and aquifer systems, modulation by deep gas degassing, and the mixing effects of multi-source fluids (Skelton et al., 2014; Kim et al., 2019; Hosono et al., 2020). Although earthquakes result from the coupling of multiple factors, most change points are identified within 45 days preceding the earthquakes. This observation suggests that component concentration changes are sensitive to earthquake preparation processes and do occur before earthquakes, which provides critical empirical support for anomaly detection algorithm models.

The BCP analysis algorithm for anomaly detection also has limitations. Compared with the  $\text{Na}^+$  detection results at WN, the  $\text{Cl}^-$  time series produces two false positives for 2022 and misses three earthquakes for 2023 (Figure 4c, d). This result suggests that the analysis requires a longer time series and is highly sensitive to prior distribution settings. In practice, identifying the locations and probabilities of earthquake induced change points in hydrochemical component time series is challenging. Larger amplitude component changes often overshadow smaller amplitude variations, which makes the latter difficult to detect and more prone to missed detections or false positives. Additionally, most BCP methods have a fundamental limitation: they inherently perform retrospective analysis on complete time series. Specifically, identifying a change point at time  $t_i$  relies on data collected after  $t_i$  ( $t > t_i$ ), which makes real time, forward earthquake forecasting unfeasible with short-term data sequences (Piersanti et al., 2016).

### 3.4.2. Anomaly detection model

According to the results of the BCP analysis, change point detection for earthquake forecasting should be viewed as a supplementary approach. Based on the change points identified by the BCP analysis across various components to guide and optimize key parameters, this study enhances the real-time anomaly detection algorithm for soil radon concentration time series (Piersanti et al., 2016; Soldati et al., 2020) and applies it to hydrochemical multicomponent time series ( $\text{Na}^+$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\delta\text{D}$ ,  $\delta^{18}\text{O}$ , etc.). The objective aim is to establish an anomaly detection model within a multi-parameter feature space to explore potential correlations between variations in hydrochemical components and

major earthquakes. This study modifies the algorithmic workflow to a backward processing mode-, enabling and enables real-time forward forecasting. In this work-the study, evaluation metrics for parameter optimisation are introduced and a seismic response time threshold parameter, which accounts for local geological conditions is incorporated. The detection model processes hydrochemical component time series and confirms earthquake catalogues, fitting optimal parameters based on the evaluation metrics to generate the best anomaly detection parameter combinations for each component. The optimised model performs online, point-by-point data processing for real-time monitoring. When real-time hydrochemical data deviates from the threshold, the model triggers an alarm to predict earthquakes, increasing which enhances forecasting accuracy through multicomponent collaboration (Figure 53). The model improves in three ways: 1) the model incorporates a multi-parameter collaborative verification mechanism that reduces environmental noise interference; 2) the model identifies components with superior anomaly detection performance; and 3) the model analyses anomaly intensity based on the number of components detecting anomalies for the same earthquake, thereby improving detection accuracy and reducing false positives and missed alarms.



**Figure 53:** Framework of the hydrochemical multicomponent synergy anomaly detection model.

The improved detection algorithm procedure (Figure S24) is described as follows: Real-time monitoring data for each component from day  $i$  are loaded. If the daily value on day  $i-p_2$  exceeds  $p_1$  times the 15-day moving average on day  $i-p_2-1$ , and simultaneously, the 15-day moving average on day  $i$  surpasses  $p_3$  times that on day  $i-p_2$ , the system triggers an alarm on day  $i$ . This alarm is considered a successful early warning if an  $M \geq 4$  earthquake occurs within  $i + T_{th}$ .

Following ~~After~~ an earthquake, new parameters  $p1' = -p4 - \times -p1$  and  $p3' = -p4 - \times -p3$  are used for a period of  $p5^M$  (where  $M$  is the magnitude). If subsequent earthquakes occur within this period, the post-earthquake time is calculated based on the maximum magnitude ~~of the subsequent earthquakes~~. If no  $M \geq 4$  earthquakes occur during this interval, parameters  $p1$  and  $p3$  automatically revert to their initial values. The algorithm incorporates five adjustable parameters ( $p1$ – $p5$ ) and a seismic response time threshold ( $T_{th}$ ), with  $p1$ ,  $p3$ , and  $T_{th}$  being key parameters.

When thermal water is subjected to external disturbances (e.g., contamination or anthropogenic inputs), particularly the dissolution of a single compound, variations in hydrochemical ion concentrations generally follow the charge balance principle, often ~~inducing resulting in~~ synchronous changes in paired cations and anions. To minimise the impact of uncertain interference and improve program efficiency, reliable warning signals should be defined by concurrent alarms from at least three hydrochemical components. The intensity of the anomaly increases with the number of components triggering simultaneous alarms.

### 3.4.3. Evaluation metrics

Given that earthquake forecasting research focuses on evaluating ~~the ability of algorithms algorithms' ability~~ to identify low-probability earthquake events, this study ~~employs-applies~~ four evaluation metrics based on the number of correct alarms (NA), false alarms (NB), and missed alarms (NC).

False alarm rate (FAR): This ~~entity~~ measures the proportion of non-earthquake events incorrectly classified as earthquake events, relative to the total number of warning instances.

$$FAR = NB / (NA + NB) \quad (7)$$

Missed alarm rate (MAR): The proportion of earthquakes that are not detected relative to the total number of earthquake events, indicating the risk of failing to identify such events.

$$MAR = NC / (NA + NC) \quad (8)$$

Probability of detection (POD): The proportion of correctly identified earthquake events out of all earthquake events, assessing the model's ability to detect these events.

$$POD = NA / (NA + NC) \quad (9)$$

Threat score (TS): This ~~variable~~ reflects the accuracy of the forecast, ranging from 0 (complete mismatch) to 1 (perfect match) with actual events.

$$TS = NA / (NA + NB + NC) \quad (10)$$

This metric system ~~allows for a more accurate evaluation of the model's forecasting performance in handling imbalanced data through multi-dimensional~~ enables a more accurate evaluation of the model's forecasting performance in handling imbalanced data via multidimensional quantitative analysis.

## 4. Results and discussion

### 4.1. Hydrochemistry

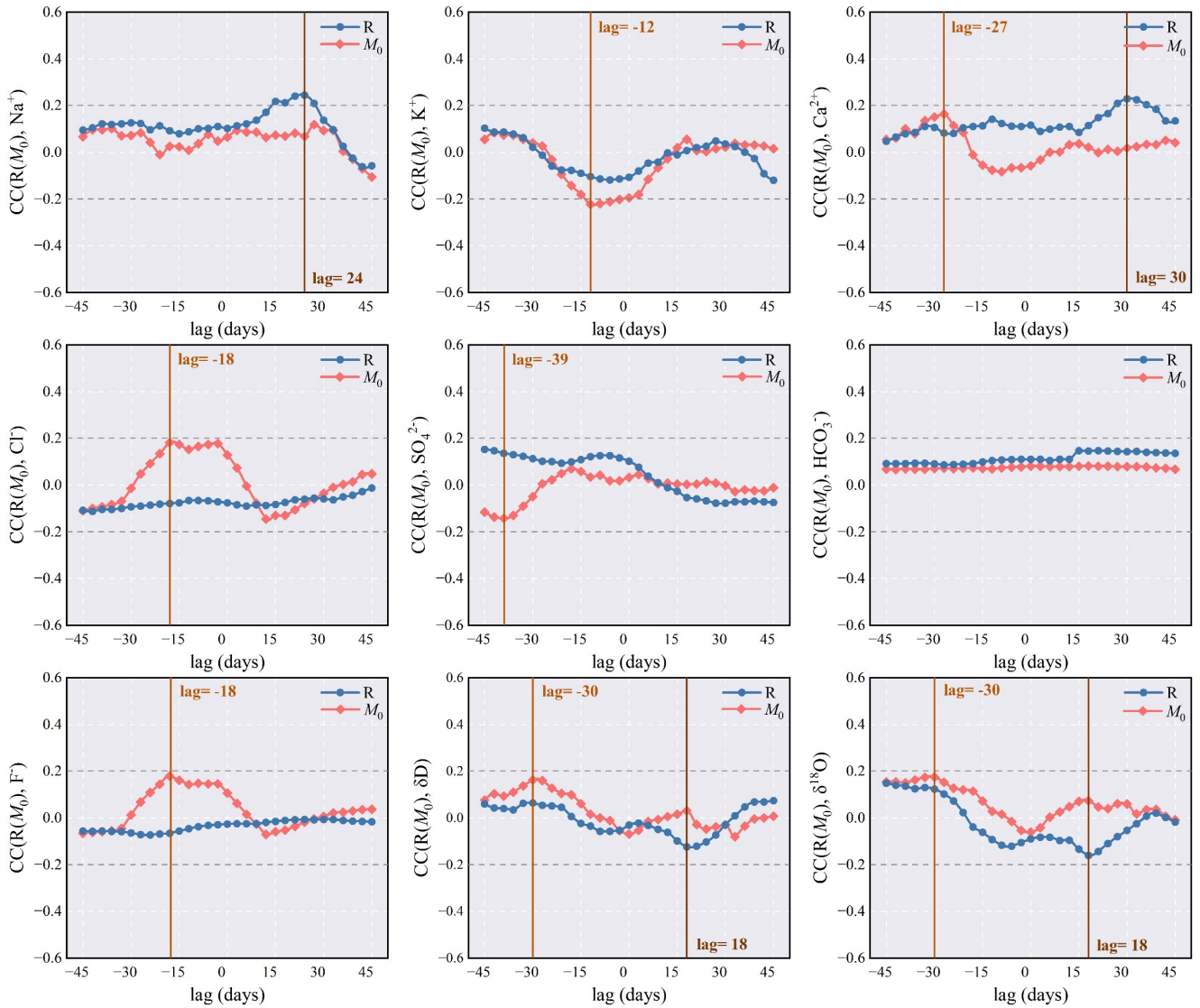
The average water temperature at QJ is approximately 60 °C, with a pH of 7.5 and an EC of 1148 μS/cm, while WN has a higher temperature of 80 °C, a pH of 7.9, and a lower EC of 579 μS/cm. Both QJ (sandstone) and WN (mylonite, gneiss, etc.) exhibit similar hydrochemical types (HCO<sub>3</sub>-Na), ~~due owing~~ to the comparable lithology of the surrounding rocks. The δ<sup>18</sup>O values at QJ range from -13.19 ‰ to -11.81 ‰, while the δD values range from -94.93 ‰ to -90.59 ‰. At WN, the δ<sup>18</sup>O values range from -13.22 ‰ to -12.01 ‰, and the δD values range from -91.26 ‰ to -88.09 ‰. The narrow fluctuation range of stable isotopes in both thermal springs, coupled with their proximity to the local and global meteoric water lines (Figure S35), ~~suggests indicates~~ that the thermal spring water originates from atmospheric precipitation. Overall, the two springs exhibit similar hydrochemical characteristics, which minimises the impact of compositional differences on the evaluation of algorithm effectiveness across the different springs. For detailed hydrochemical ion concentrations and isotope values, please refer to the supplementary materials.

### 4.2. Hydrochemical responses

The cross-correlation analysis findings (Figure 4) show weak correlations (blue dotted lines) between rainfall events and the 15-day moving average hydrochemical component time series, with correlation coefficients approximately within ± 0.2. This result indicates that the moving average treatment effectively mitigates rainfall-induced noise. To validate the robustness of the denoising process, the results obtained from the moving average were compared with those derived from Fast Fourier Transform low-pass filtering and wavelet-based denoising techniques (Figure S6). The approximately consistent outcomes across all methods confirm the suitability of the moving average approach for suppressing high-frequency noise. Furthermore, this method is better suited to the model's real-time anomaly detection framework. Notably, Na<sup>+</sup>, Ca<sup>2+</sup>, δD, and δ<sup>18</sup>O exhibit minor response peaks at lags of 18–30 days, suggesting that these components remain continuously affected by rainwater infiltration within 15–30 days after precipitation. Similarly, the correlations between

the distance-corrected  $M_0$  and the denoised hydrochemical component time series (red dotted lines) remain low (around  $\pm 0.2$ ). However,  $K^+$ ,  $Ca^{2+}$ ,  $Cl^-$ ,  $SO_4^{2-}$ ,  $F^-$ ,  $\delta D$ , and  $\delta^{18}O$  exhibit weak response peaks at lags of  $-39$  to  $-12$  days, with varying peak directions for each component. This observation suggests that seismic activity (12–39 days before seismic moment release) may influence hydrochemical components, causing their concentrations to fluctuate (either increasing, decreasing, or remaining stable) due to different geochemical mechanisms.

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**Figure 34: Cross-correlation function analysis of the 15-day moving average time series of hydrochemical components during stable isotope monitoring, with rainfall and distance-corrected seismic moment.**

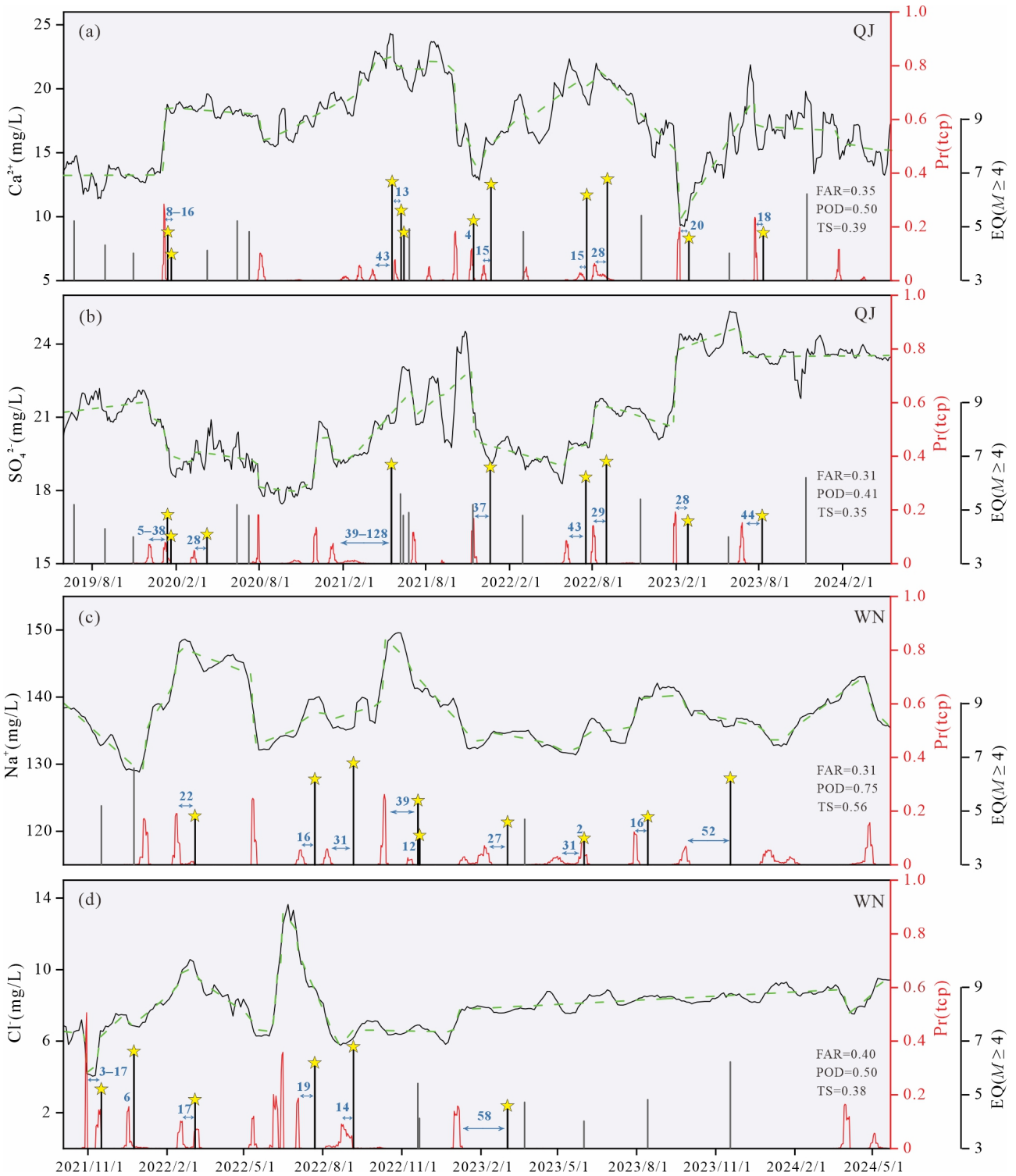
### 4.3. BCP detection of pre-earthquake anomalies

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Cross-correlation analysis revealed the hydrochemical responses preceding seismic moment release, while BCP analysis further captured these anomalous signals and identified their timing. The results show that change points are successfully

420 detected in all component time series from both thermal springs (Figure 5). Consistent with geological precursor studies, where low-probability signals are often retained due to the weak intensity of hydrochemical anomalies. For example, before the *M*6.6 earthquake on 24 December 2021, the posterior probability for a  $\text{Ca}^{2+}$  change point at QJ was 0.06 at 15 days before the earthquake, while  $\text{SO}_4^{2-}$  exhibited a posterior probability of 0.17 at 37 days before the earthquake. Similarly, before the *M*5.2 earthquake on 16 November 2021,  $\text{Cl}^-$  at WN showed posterior probabilities for change points of 0.15 and 0.51 at 3 and 17 days before the earthquake, respectively. Notably, most change points are identified within 45 days preceding the earthquakes. This observation suggests that component concentration changes are sensitive to earthquake preparation processes and occur before earthquakes, which provides critical empirical support for anomaly detection algorithm models.

425 Notably, the timing and posterior probabilities of change points exhibit significant uncertainty, reflecting the complexity of factors influencing variations in hydrochemical components. These factors include inhomogeneity in stress accumulation, the structural complexity of fault and aquifer systems, modulation by deep gas degassing, and the mixing effects of multi-source fluids (Skelton et al., 2014; Kim et al., 2019; Hosono et al., 2020). In particular, the variable dominance of different mechanisms (e.g., water-rock interaction and fluid mixing) in different earthquake cases leads to inconsistent timing and intensity of hydrochemical anomalies, thereby causing uncertainty in BCP-detected change points. Among these complex factors, well-established mechanisms like water-rock interaction and fluid mixing can effectively explain several detected anomalies. For instance, the rise in  $\text{Na}^+$  concentrations before earthquake may result from a switchover to nonstoichiometric dissolution of analcime at fresh rock surface with preferential release of  $\text{Na}^+$  into groundwater (Andr n et al., 2016). 430 Similarly, the increase in  $\delta^{18}\text{O}$  before the *M*6.6 Tottori earthquake in southwestern Japan has been attributed to enhanced water–rock interaction due to rock strain during the earthquake preparation process (Onda et al., 2018). Furthermore, the mixing of fluids with significantly different isotopic and hydrochemical compositions can cause variations in  $\delta\text{D}$ ,  $\delta^{18}\text{O}$ , and ion concentrations. Previous studies in Iceland have reported pre-earthquake increases in  $\text{Na}^+$  concentration,  $\delta\text{D}$ , and  $\delta^{18}\text{O}$  due to mixing with different groundwater (Skelton et al., 2014, 2024). A similar phenomenon is observed in the elevated 440 EC and ion concentrations preceding the *M*w5.0 Mudanya earthquake in western Turkey (Yakupog lu et al., 2025).



**Figure 45: Anomaly detection results from the Bayesian change point (BCP) analysis applied to hydrochemical component time series. The black solid line represents the component concentration after 15-day moving averaging. The green dashed line indicates the forecasting model of the BCP algorithm. The red solid line shows the posterior probability of change points. Yellow stars mark earthquake events. Black and gray vertical bars indicate detected and missed earthquakes, respectively. The false alarm rate (FAR), probability of detection (POD), and threat score (TS) are evaluation metrics; further details are provided later.**

Compared with the  $\text{Na}^+$  detection results at WN, the  $\text{Cl}^-$  time series produces two false positives for 2022 and misses three

450 earthquakes for 2023 (Figure 5c, d). This result suggests that the analysis requires a longer time series and is highly sensitive to previous distribution settings. Larger-amplitude component changes often overshadow smaller-amplitude variations, which makes the latter difficult to detect and more prone to missed detections or false positives. In addition, most BCP methods have a fundamental limitation: they inherently perform retrospective analysis on complete time series. Specifically, identifying a change point at time  $t_i$  relies on data collected after  $t_i$  ( $t > t_i$ ), making real-time, forward earthquake forecasting unfeasible with short-term data sequences (Piersanti et al., 2016). According to the BCP analysis results, change-point detection for earthquake forecasting should be viewed as a supplementary approach for anomaly detection model to locate  
455 anomaly timing, guide parameter optimization, and conduct comparative verification.

#### 4.42. Model parameters

##### 4.42.1. Seismic response time threshold

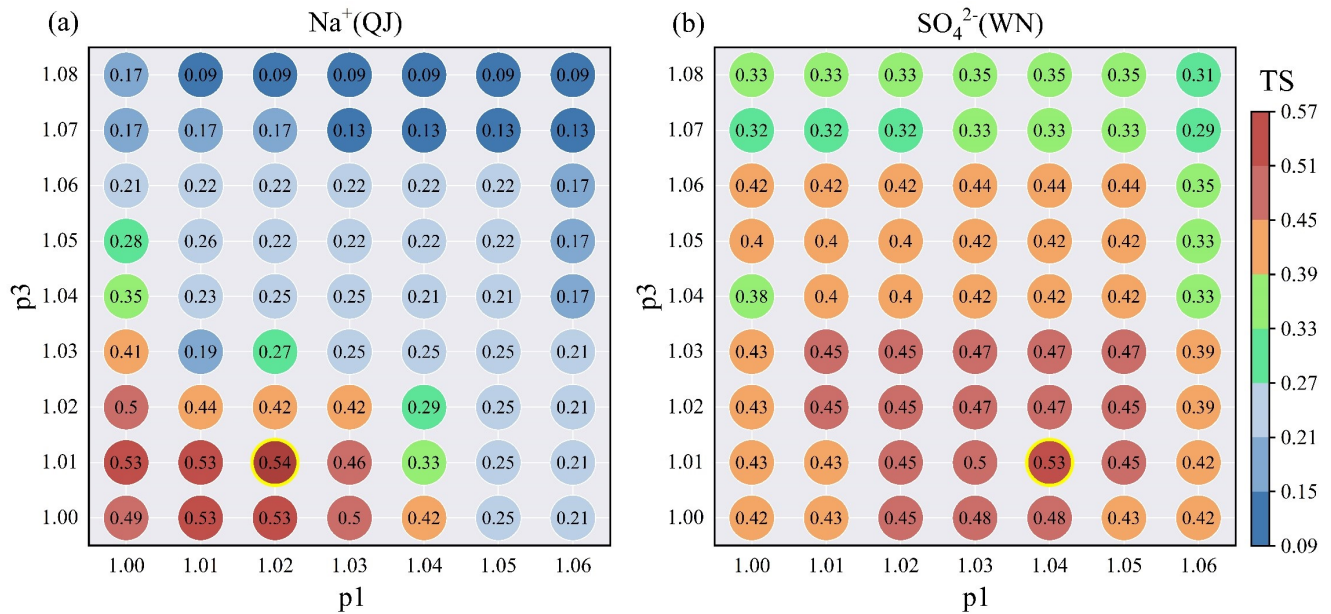
The anomaly detection model in this study establishes forecasting rules based on the temporal correlation between precursor anomalies and earthquake events. The seismic response time threshold ( $T_{th}$ ) plays a ~~crucial key~~ role in  
460 determining both forecasting performance and practical value.  $T_{th}$  is defined as the maximum allowable time interval between anomaly detection and earthquake occurrence. This threshold is a critical parameter that ~~strikes a balance~~ between accuracy and timeliness. Increasing  $T_{th}$  expands the monitoring window and captures more potentially correlated abnormal signals, but it ~~considerably significantly~~ reduces the time resolution of forecasting. Conversely, decreasing  $T_{th}$  ~~enhances improves~~ temporal precision but may risk omitting valid precursor signals owing to shorter observation periods.

465 To improve the accuracy of the anomaly detection model in predicting earthquake timing, the nonlinear effects of  $T_{th}$  on predictive performance are systematically explored via an incremental increase of  $T_{th}$  from 5 to 70 days in 5-day steps. This increase ~~determines~~ identifies key inflection points during threshold optimisation (Figure S47). As  $T_{th}$  increases from 5 to 45 days, ~~the~~ model performance improves considerably, with both TS and POD rising rapidly, while FAR gradually decreases. This improvement results from the extended monitoring windows, which ~~more effectively~~ better capture the  
470 association between anomalies and seismic activities. Notably, the evaluation metrics reveal a turning point at the 45-day threshold. Beyond 45 days, the trends in TS, POD, and FAR plateau, ~~show with~~ minimal variations. This result is consistent with the finding that maximum cross-correlations between  $M_0$  and hydrochemical components ( $Cl^-$ ,  $SO_4^{2-}$ , and  $\delta D$ ) occur within 45 days before the earthquake (Figure 34) and that BCP analysis detects most change points emerging within 45 days of pre-earthquake events (Figure 45). Collectively, these results jointly define 45 days as the optimal response time

475 threshold for hydrochemical precursors to seismic activities in the study ~~region~~area.

#### 4.4.2.2. Free parameters

The parameter optimisation process involves quantitatively aligning observed hydrochemical data with seismic precursor anomalies. Among the five adjustable parameters (p1–p5) in the detection model, the key regulatory parameters p1 and p3 represent multiples of the sliding window values. This study ~~emphasises~~ ~~focuses~~ on p1 and p3 to examine the ~~impact~~ ~~influence~~ of ~~optimising~~ ~~the optimisation of~~ these parameters on the performance of the anomaly detection model. ~~The~~ parameter ranges were based on specific seismological rationale, operational framework of model, and actual model ~~performance test results~~. For optimisation involving ion concentration data, the model applies parameter values ranging from 1.00 to 1.20 in steps of 0.01. For optimisation involving isotopic data, which exhibit minor fluctuations, the model applies parameter values ranging from 0.985 to 1.015, with a step increment of 0.001. ~~The model's~~ ~~Model~~ performance is then evaluated using TS, ~~which is employed as the primary metric due to its comprehensive integration of NA, NB, and NC, making it particularly suitable for evaluating model performance on imbalanced data~~. Figure 6 shows the variations in the TS under different values of p1 and p3. When p1 and p3 are small, the model becomes overly sensitive to background noise, ~~resulting in the detection of~~ ~~detecting~~ more non-seismic signals. This effect leads to an increase in the FAR and a decrease in TS. ~~TS improves with the rise in As~~ p1 and p3 ~~increase, TS improves~~. However, when the parameters become ~~excessively large, surpassing the actual seismic anomaly thresholds, the MAR rises sharply, which causes TS to drop below 0.35. The optimal parameter combinations for each hydrochemical component are identified at the TS peak inflection points (marked by yellow circles). The results for all evaluation metrics under varying parameters (p1 and p3) for Na<sup>+</sup> at QJ and for SO<sub>4</sub><sup>2-</sup> at WN are provided in Table S2 and Table S3, respectively. According to this method, the complete set of model parameters for all hydrochemical components at QJ and WN is provided in Table S24.~~



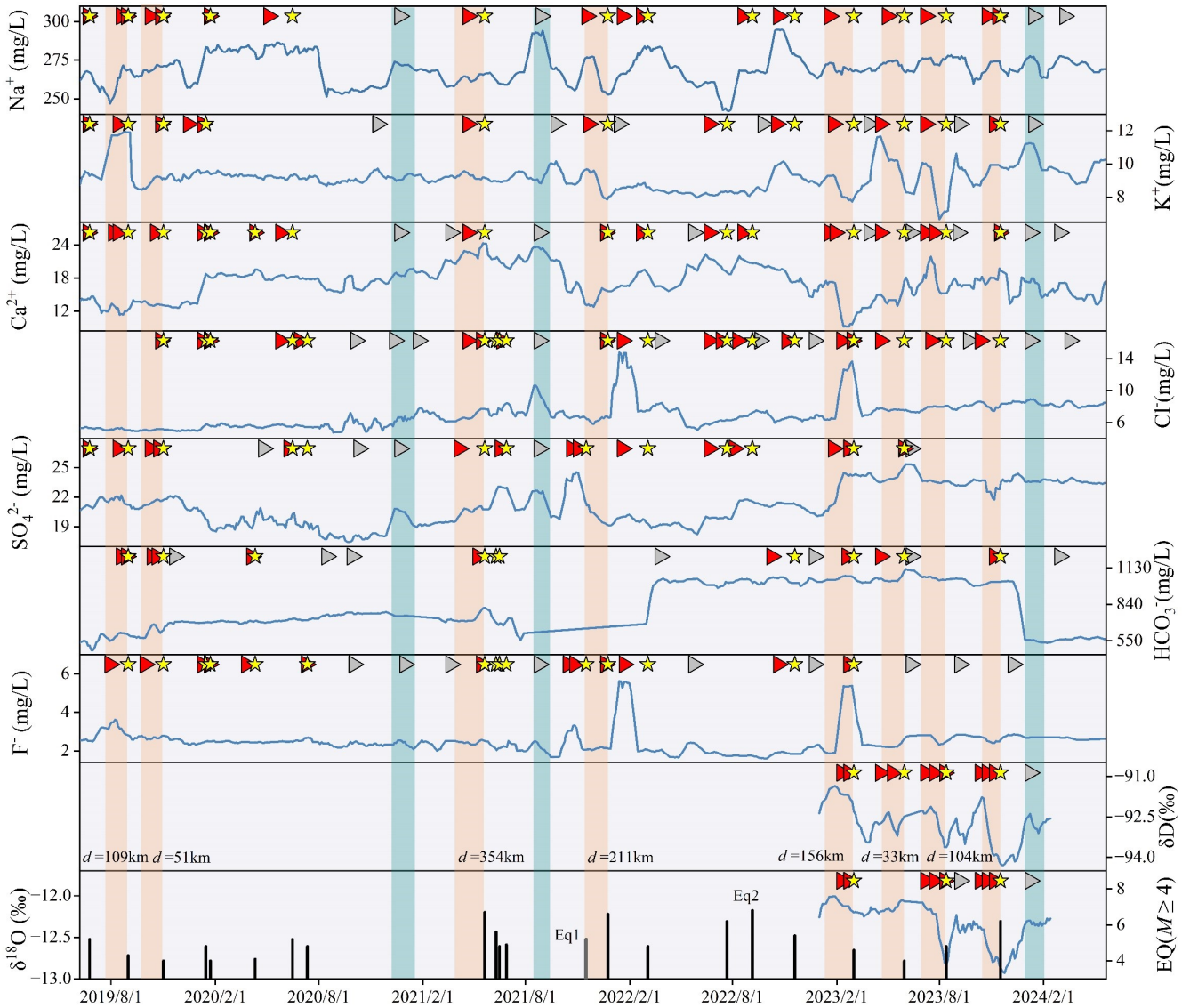
**Figure 6: Effect of parameters on model performance. TS varies with changes in p1 and p3 (the main free parameters p1 and p3 are used as examples). The yellow circle highlights the TS value corresponding to the optimal combination of p1 and p3.**

The parameter optimisation results reveal notable differences in the optimal p1 and p3 combinations for different hydrochemical components. Hydrochemical anomalies preceding earthquakes in many regions are typically caused by the combined action of multiple mechanisms (Skelton et al., 2014; Kim et al., 2019; Hosono and Masaki, 2020). Furthermore, due to significant variations in the geochemical behavior of different hydrochemical components, components within the same thermal spring often exhibit diverse response patterns to the same earthquake. These patterns may include asynchronous variations (increase/decrease/stability) and considerable discrepancies in the magnitude of change (Shi et al., 2020; Wang et al., 2021; Tian et al., 2023). Therefore, optimising parameter combinations to create customised anomaly detection models for specific hydrochemical components at designated observation points is the critical key approach in this study to enhance the model's ability to detect seismic precursor information.

#### 4.5.3. Evaluation of forecasting performance

Figures 7 and 8 present the 15-day moving average time series of hydrochemical components, anomaly detection results, and earthquake events for the anomaly detection model at QJ and WN. For each component, the model successfully identifies varying numbers of pre-earthquake anomalies and triggered warnings. The model activates comprehensive alarms when anomalies are detected in three or more components simultaneously. At QJ, the model provides 21 effective warnings for 22 earthquake events (POD = 0.95), with 8 false alarms (FAR = 0.28) and a TS of 0.70. At WN, the model

generates 10 accurate warnings for 12 events (POD = 0.83), 5 false alarms (FAR = 0.33), and a TS of 0.59. It is noteworthy that although the obtained FAR remains relatively high, which is a common challenge in earthquake anomaly detection that prioritises detection sensitivity, the TS provides a comprehensive metric that balances both POD and FAR. Compared with the internal single-component anomaly detection results from our model, the multi-component joint warning results exhibit higher TS values (Figures 7, 8, 9). This observation demonstrates that multicomponent collaboration mitigates the effects of geochemical behavior differences among components, reduces environmental interference on individual ions/ion pairs, and consequently enhances the accuracy of the anomaly detection model. Zhu et al. (2024) comprehensively evaluated the anomaly detection performance of several machine learning algorithms using 2.5 years of hydrochemical data from the southeast coast of China. The best-performing local outlier factor algorithm achieved an R-score of about 0.6, POD of about 0.7, and FAR of about 0.15. The improved anomaly detection model demonstrates comparable performance, which confirms its effectiveness. These results indicate the practical value of the multi-component model for anomaly identification, though its practical application would benefit from integration with other geophysical, geodetic, and geological data to further reduce the false alarm burden. The results from the anomaly detection model and BCP analysis are mutually corroborative; however, the anomaly detection model exhibits superior sensitivity in processing nonlinear time series data. Taking QJ as an example, the model achieves POD values of 0.70 and 0.59 for  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  detection results, respectively (Figures 4 and 7), which represent significant improvements over the BCP analysis results (0.50 and 0.41). The model is also capable of accurately detecting subtle anomalies that the BCP analysis may miss.



**Figure 7: Results of the anomaly detection model applied to hydrochemical component time series from Qujiang spring. The blue curve represents the hydrochemical component time series after a 15-day moving average. Red and gray triangles indicate accurate alarms and false alarms, respectively. Yellow stars mark successfully reported earthquakes. Black and gray vertical bars depict show detected and missed earthquakes based on the algorithm's comprehensive alarm (triggered by  $\geq 3$  components), respectively. Orange-red boxes highlight synchronous successful alarms triggered by six or more components. Grayish-blue boxes mark synchronous false alarms triggered by five or more components.**

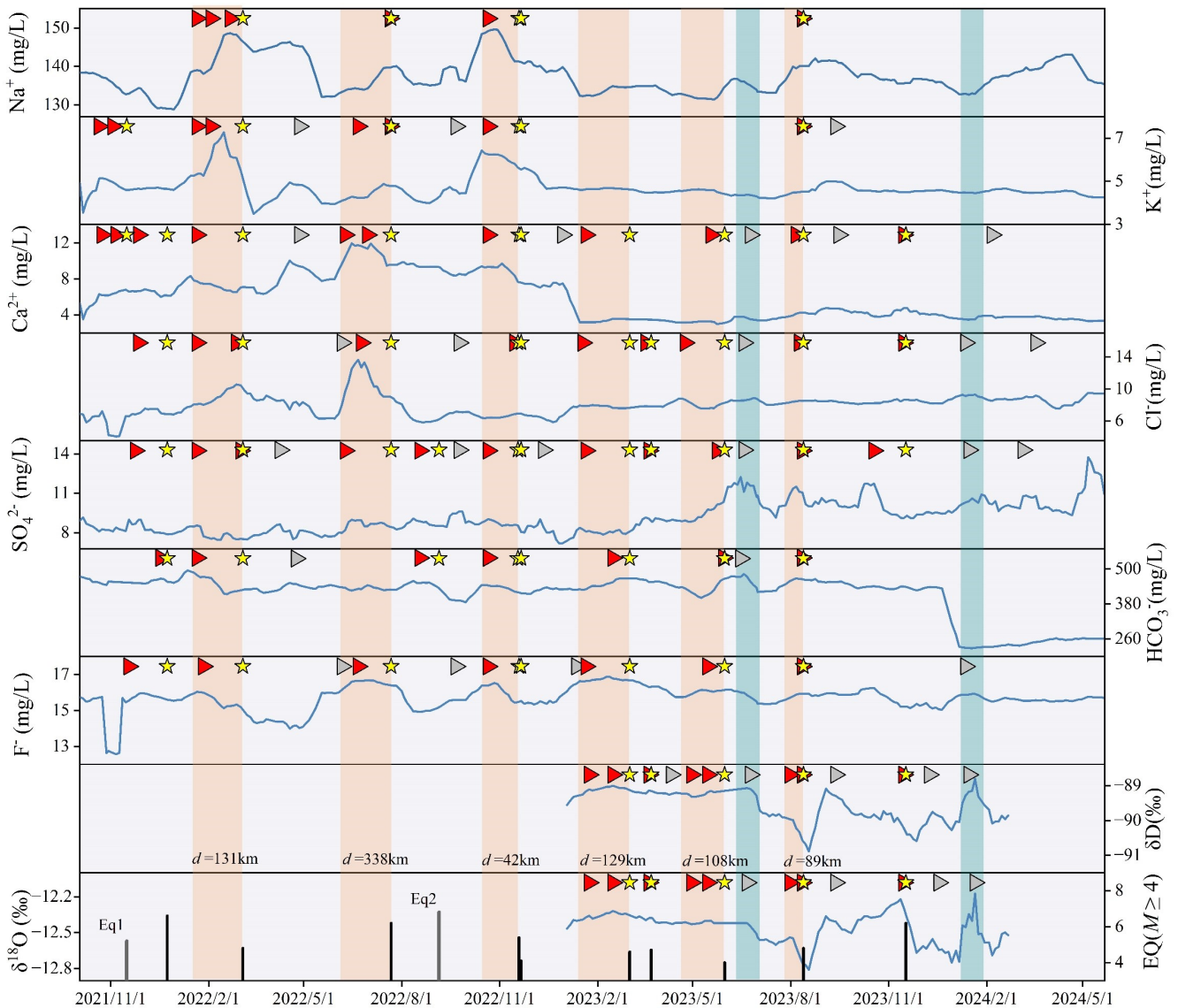
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Owing to variations in the geochemical behaviors of hydrochemical components, their response patterns and magnitudes to earthquakes differ. Although the mechanisms behind these differences have not yet reached academic consensus, this study aims to identify effective indicators for strong earthquake forecasting prediction indicators applicable to the study area through the results of anomaly detection model results. A comparison of the TS values of each component's warning results in QJ and WN (Figure 9) reveals that in the two thermal springs of the study area, the TS values for  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\delta\text{D}$ , and  $\delta^{18}\text{O}$  detection (around 0.50) are relatively high. This observation suggests that these components can serve

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545 as sensitive indicators for strong earthquake forecasting in the study area. In general, QJ in the study area exhibits a more sensitive response to earthquakes. In addition, the anomalies are categorised into multiple consecutive anomalies and single anomalies (Figures 7 and 8). This phenomenon is more pronounced in the stable isotope time series, likely because isotopic changes are more sensitive and tend to trigger multiple warning signals before an earthquake. **The higher sensitivity of  $\delta D$  and  $\delta^{18}O$  may be attributed to the fact that stable water isotopes are more conservative than hydrochemical ions, meaning they typically track water sources and mixing without being significantly affected by short-term water-rock interactions** (Skelton et al., 2014, 2024; Su et al., 2025). **The hydrochemical ions are easily altered by short-term chemical processes, such as dissolution or precipitation, cation exchange, adsorption or desorption, and redox reactions, making their signals more complex.**

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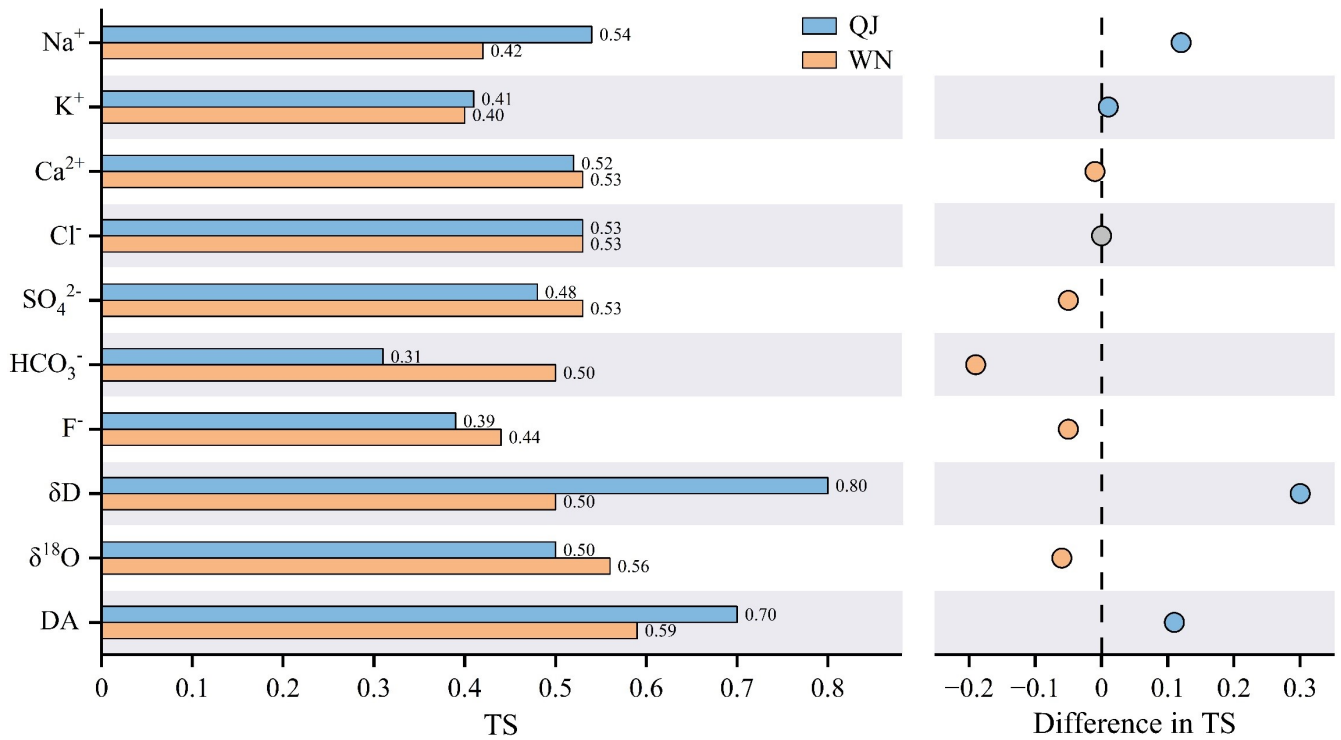


**Figure 8: Results of the anomaly detection model applied to hydrochemical component time series from Wana spring. The**

555 same notes as above for Figure 7.

Among the earthquakes for which the earthquake preparation zone covers both thermal springs, only two earthquakes (represented by gray vertical bars in Figures 7 and 8) fail to induce multicomponent anomalies before prior to the earthquake. Earthquake Eq1 causes no synchronous anomalies at either spring, which suggestings that Eq1 has a limited impact on regional tectonic activity. For Eq2 (epicentral distance > 600 km), WN shows no alarm response, while QJ reacts effectively. This discrepancy is likely related to WN's location on the eastern boundary of the SYB, where stress accumulation mainly affects QJ, which is also located on the eastern border. The muted response in WN is likely attributed to likely results from the blocking effects of the RRF (Li et al., 2024; Shao et al., 2024). The similar abnormal response sensitivity of different springs to the same earthquake demonstrates regional-scale hydrochemical impacts from earthquake preparation and confirms the stable and reliable performance of the anomaly detection model.

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**Figure 9: TS values of anomaly detection model results for hydrochemical components. DA denotes comprehensive alarms triggered by the model.**

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In Figures 7 and 8, the orange-red boxes represent model results of successfully predicted earthquakes, identified through synchronised anomalies in six or more hydrochemical components. The width of the boxes, which indicates the interval between the appearance of anomalies and earthquake occurrence, shows no clear correlation with magnitude or epicentral distance. This observation highlights underscores the complex dynamic mechanisms and regional structural differences

that are involved in the earthquake preparation process, ~~with anomalies often arising from the combined effects of multiple mechanisms (Thomas, 1988).~~ The geochemical anomalies often arise from the combined effects of multiple mechanisms, such as fluid mixing following aquifer breaching or fresh mineral surface exposure during micro fracturing, resulting in increased concentrations of hydrochemical component (Thomas, 1988). Spatially, the number of hydrochemical components exhibiting synchronous anomalies correlates with earthquake magnitude and epicentral distance. Earthquakes that induce synchronous anomalies in six or more hydrochemical components have epicentral distances of less than ~~within~~ 150 km for earthquakes with magnitudes less than 6.0 ( $M < 6.0$ ), while this distance extends to approximately 450 km for earthquakes with magnitudes greater than or equal to 6.0 ( $M \geq 6.0$ ). Although it is difficult to quantify the exact impact of magnitude and distance on the number of components exhibiting synchronous anomalies, as magnitude increases or distance decreases, the number of components with synchronous anomalies detected by the model tends to increase. This trend aligns with the positive correlation between the scale of earthquake energy release and the number of anomalies, as confirmed by the hydrochemical monitoring results (Li et al., 2022). Therefore, a significant relationship ~~is present~~ exists between the temporal variation of hydrochemical components and earthquakes in the study ~~region~~ area. The number of components exhibiting synchronous anomalies can be used as an effective criterion for determining alarm intensity, with higher intensity generally corresponding to larger earthquake magnitudes or shorter epicentral distances.

Furthermore, this study reveals that hot springs closer to the ~~epicentre~~ ~~epicenter~~ tend to exhibit a greater number of components with synchronous anomalies during the same earthquake. Pre-earthquake hydrochemical anomalies generally manifest on a regional scale, which means different thermal springs can not only validate each other in terms of anomaly timing for forecasting purposes but also help identify the closest springs to the ~~epicentre~~ ~~epicenter~~ based on the number of synchronous anomalous components. This approach ~~helps define~~ ~~aids in defining~~ potential earthquake preparation zones. According to this approach, a dense thermal spring monitoring network provides more opportunities for spatial earthquake forecasting.

#### 4.64. Limitations and prospects

This study focuses on evaluating the performance of anomaly detection models in predicting the timing of earthquakes with magnitudes  $\geq 4$ . One potential cause of false alarms could be anomalous fluctuations in hydrochemical components triggered by seismic activities with magnitudes  $< 4$  in areas near thermal springs. Four days after the second synchronised false alarm involving five components (Figure 7, grayish-blue boxes), an  $M$ -2.6 earthquake occurred 3 km from QJ. This

600 occurrence suggests that high-frequency false alarms may not solely result from non-seismic fluid anomalies, but could also reflect the model's limited ability to distinguish anomalies caused by microseisms. According to this finding, it is recommended to establish observation station networks and optimise algorithms to enable hierarchical alarm systems. Approximately 30 days after the last multicomponent synchronised false alarms at the two thermal springs (Figures 7 and 8), an  $M=4.1$  earthquake occurred, with an ~~epicentre~~~~epicenter~~ located outside the radius of the earthquake preparation zone. The ~~c~~Current earthquake screening ~~criteria~~~~method~~ assume an isotropic underground structure ~~although effective and widely used.~~~~however~~, Therefore, the algorithm requires special optimisation based on the specific geological background ~~in practical applications in further research~~. Additionally, the model demonstrates limited adaptability to changes in data trends, highlighting the need for periodic parameter re-optimisation. ~~Although~~~~While~~ the model is constructed using major elements and stable isotopic indicators in thermal waters, future research should also consider the potential associations between other hydrochemical components, such as trace elements, and seismic activity.

610 Due to significant differences in hydrogeological settings, tectonic activity, and the current limitations in quantitatively modeling geothermal water circulation under specific geological conditions, a universal set of model parameters applicable across all hot springs within even the same tectonic region cannot be established. This phenomenon highlights the necessity of anomaly detection model, which involves optimizing parameters specifically for individual hot springs based on their unique pre-seismic responses in different hydrochemical components. The model aims to leverage the inherent differences among these hydrochemical components, integrating them to enhance forecasting efficacy. Crucially, this methodological framework is transferable. For application in other tectonic regions, the model can be adapted by similarly optimizing the parameter combinations for the target hot springs based on their specific hydrochemical components. This outcome addresses the challenge posed by varying tectonic and hydrogeological conditions, which lead to divergent hydrochemical behaviors. By enabling the model's applicability to hot spring monitoring in specific regions through this targeted parameter optimization, the model provides a valuable reference for earthquake forecasting.

## 5. Conclusions

A multicomponent synergistic anomaly detection model is developed using five years of continuous hydrochemical monitoring data to enable real-time forecasting of  $M \geq 4$  earthquakes in the study area. Model parameters are optimised for each component, and their impact on anomaly detection performance is evaluated to identify applicable hydrochemical

625 indicators for strong earthquake forecasting. The ~~results of the~~ multicomponent synergy anomaly detection ~~findings~~ reveal a clear connection between hydrochemical variations and seismic activity, offering valuable insights, and establishing a new paradigm for precursor identification in earthquake forecasting. The main findings are summarised as follows:

- 630 1. A 45-day response time threshold for hydrochemical components to  $M \geq 4$  earthquakes is established as the optimal period for capturing ~~critical key~~ hydrochemical precursors for short-term earthquake forecasting. ~~Tailored model parameters for specific hydrochemical components account for their differences in response characteristics to seismic activity and~~ Parameters are optimised for individual components based on their distinct geochemical responses to seismic stress, significantly enhancing the model's performance and adaptability.
- 635 2. The anomaly detection model demonstrates reliable real-time anomaly detection capabilities, with its overall performance characterized by POD ranging from 0.83 to 0.95 and TS between 0.59 and 0.70. It also displays similar anomaly detection results across different springs in response to the same earthquake. ~~and~~ The model identifies  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\delta\text{D}$ , and  $\delta^{18}\text{O}$  as effective indicators for ~~strong~~ earthquake forecasting, all of which exhibit outliers before earthquakes, with TS above 0.50 at the individual indicator level. Among these, ~~with~~  $\delta\text{D}$  and  $\delta^{18}\text{O}$  exhibiting higher sensitivity to seismic activity, characterized by multiple consecutive anomalies pre-ceding an earthquake.
- 640 3. The newly proposed ~~multicomponent-parameter~~ synergy alarm mechanism for hydrochemistry overcomes the limitations of single-parameter methods and ~~substantially significantly~~ improves the model's overall performance in earthquake forecasting. The number of hydrochemical components with synchronous anomalies provides a reliable criterion for determining alarm intensity, with higher intensity typically correlating to larger earthquake magnitudes or shorter epicentral distances. A dense thermal spring monitoring network can facilitate cross-verification across multiple sites for time-based forecasting and offer enhanced capabilities for spatial forecasting.

#### 645 **Data availability**

The continuous monitoring data from thermal springs can be found at Mendeley Data, Version 1 (<https://10.17632/xkd75cyfmb.1>).

#### **Author contributions**

650 WS: conceptualization, formal analysis, investigation, methodology, software, validation, visualization, writing original draft. YL: conceptualization, funding acquisition, methodology, project administration, supervision, review and editing.

XZ: data curation, funding acquisition, investigation, project administration, resources. ZC: supervision, validation. HL: methodology, software. ZL: visualization, review and editing. CL: supervision, review and editing. YW: data curation, resources, validation. ZZ: data curation, resources, validation. YW: investigation, supervision. HH: visualization, review and editing. SF: investigation.

## 655 **Competing interests**

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.

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