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Decoding multicomponent hydrochemical anomalies: a synergistic detection model for earthquake forecasting

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Supplementary Information for Figure

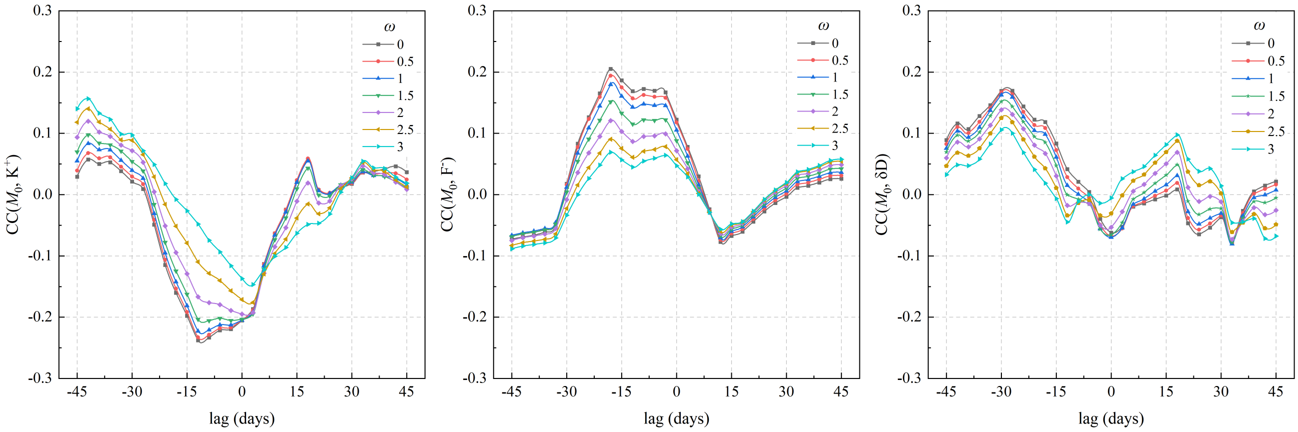

Figure S1: Cross-correlation function analysis of the 15-day moving average time series (K^+, F^-, δD) and distance-corrected seismic moment for multiple ω values (including 0, 0.5, 1, 1.5, 2, 2.5, and 3).

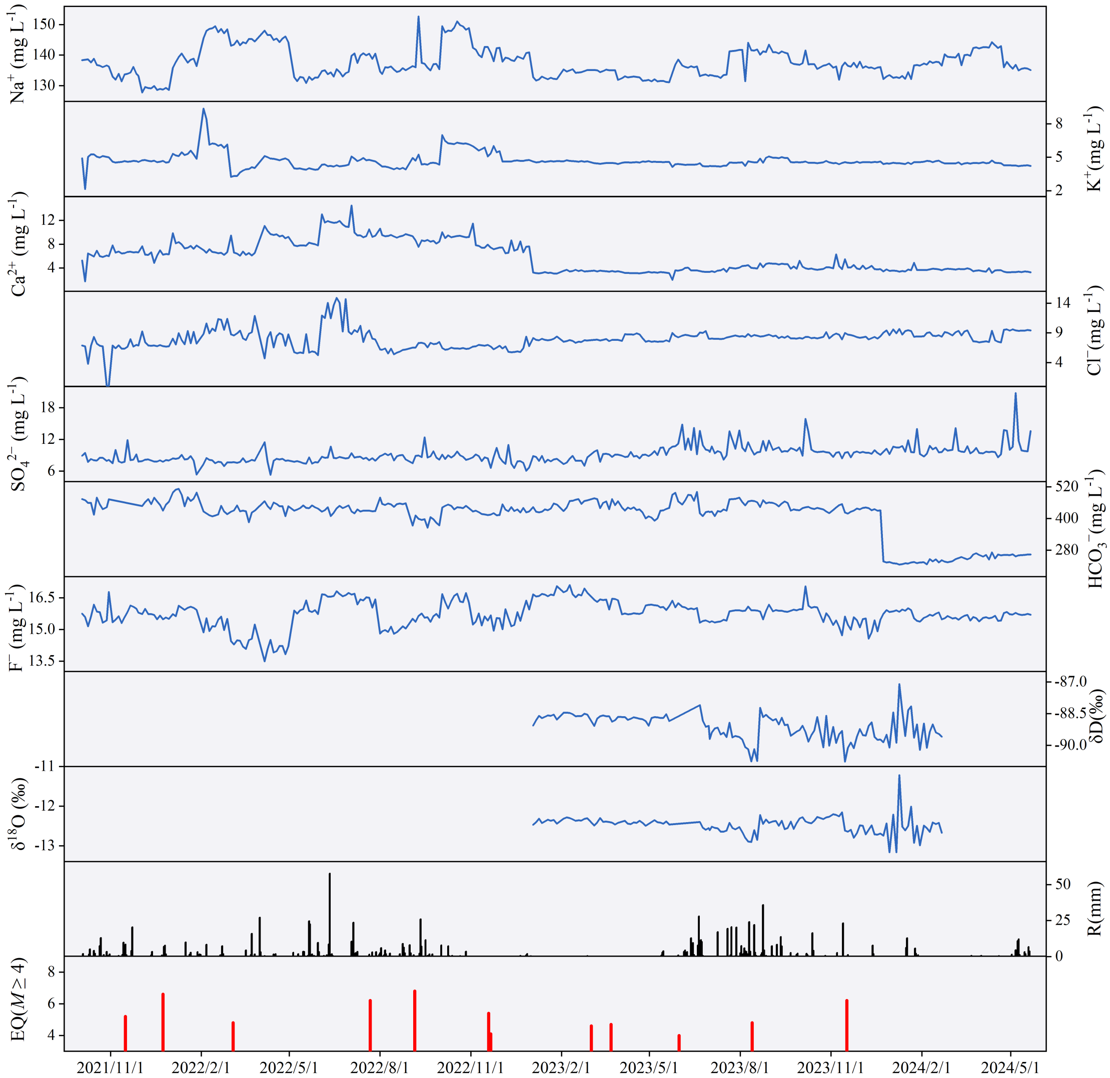

Figure S2: Time series of hydrochemical components (Na^+, K^+, Ca^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, F^-, δD, and $\delta^{18}O$), alongside corresponding rainfall and earthquake events for Wana spring.

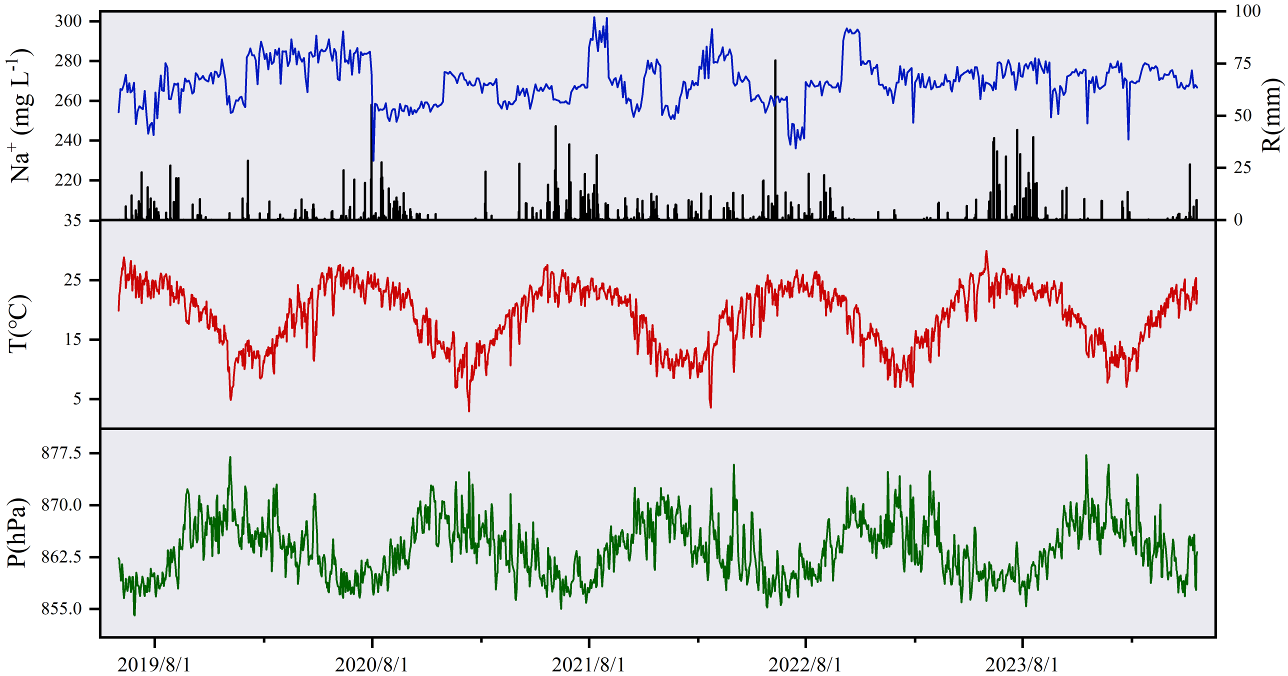

Figure S3: Time series of Na^{+}, alongside corresponding rainfall (R), temperature (T), and atmospheric pressure (P) for Qujiang spring.

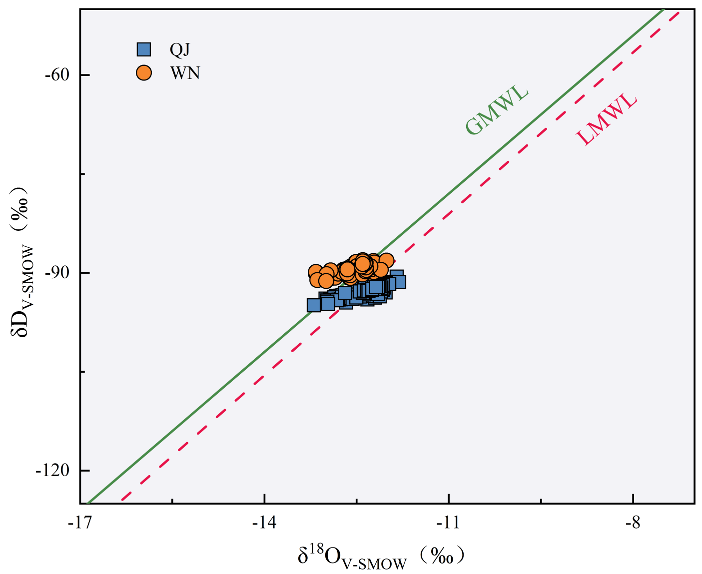

Figure S4: Plot of δD versus $\delta^{18}O$ for thermal springs. GMWL: Global Meteoric Water Line (Craig, 1961); LMWL: Local Meteoric Water Line (Li et al, 2016).

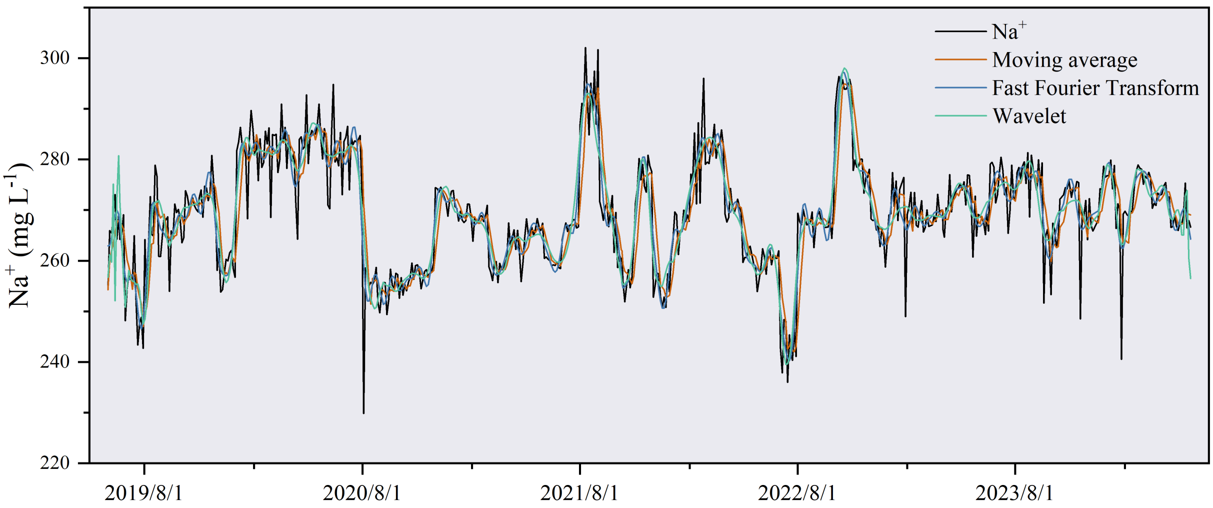

Figure S5: Comparison of denoising results using 15-day moving average, Fast Fourier Transform, and 3-level Wavelet (using DB5 wavelet with 20 % threshold).

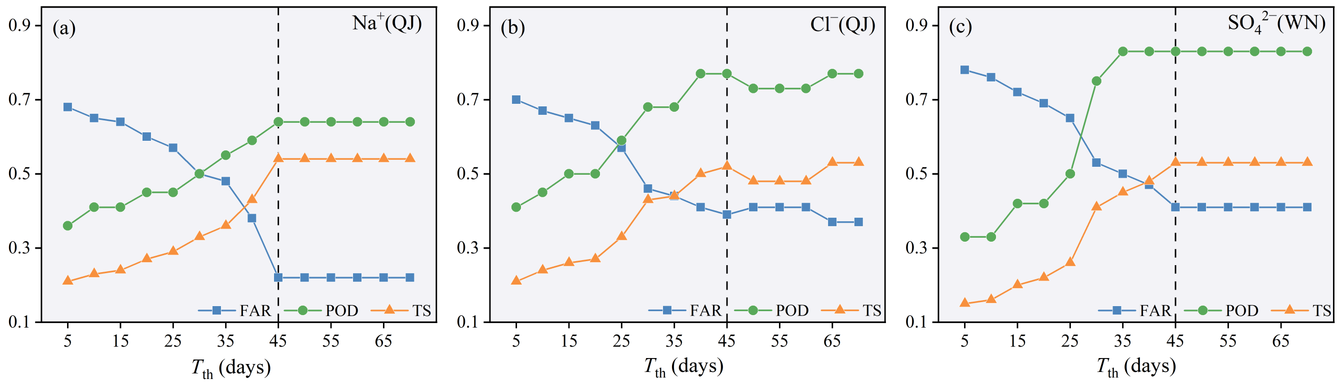

Figure S6: Variations in the false alarm rate (FAR), probability of detection (POD), and threat score (TS) as a function of the seismic response time threshold (T_{th}).

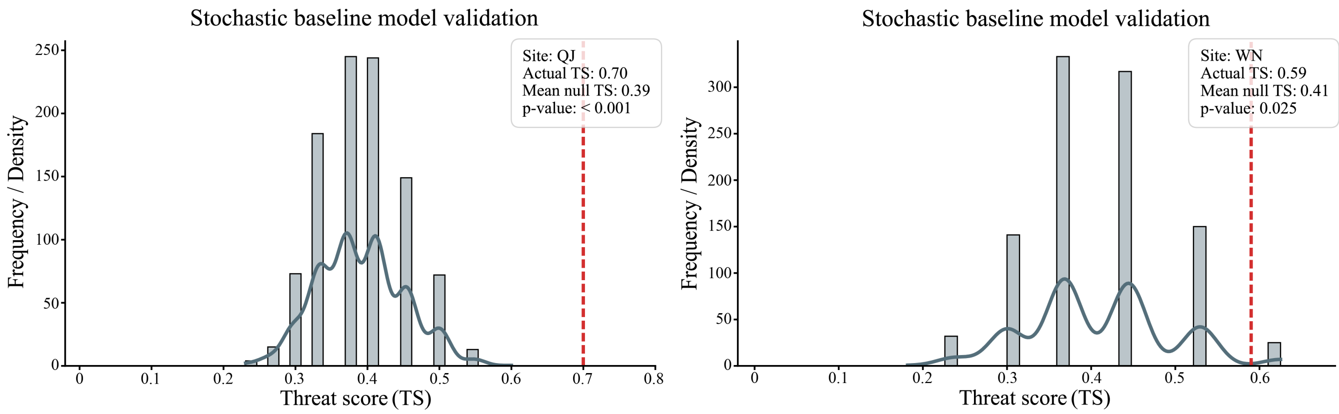

Figure S7: Statistical significance and model performance reliability validation. The histograms illustrate the TS distribution of the stochastic baseline model (1,000 Monte Carlo iterations), while the red dashed lines mark the actual performance of the proposed model at sites Qujiang (QJ) and Wana (WN) springs, respectively.

Supplementary Information for Table

Table S1: Catalog of earthquakes meeting the selection criteria during the thermal spring monitoring period.

Date	Lon.	Lat.	Depth (km)	*M*	Δ (km)		Response sites
					QJ	WN	
2019/06/24	101.64	24.93	10	5.2	161	—	QJ
2019/08/31	101.95	23.34	13	4.3	109	—	QJ
2019/11/01	102.79	24.39	13	4.0	51	—	QJ
2020/01/15	103.12	25.55	8	4.8	182	—	QJ
2020/01/23	101.86	23.37	15	4.0	115	—	QJ
2020/04/11	101.89	23.67	12	4.1	97	—	QJ
2020/06/16	102.72	22.64	9	5.2	144	—	QJ
2020/07/12	102.52	22.86	11	4.8	123	—	QJ
2021/05/21	99.88	25.70	10	6.7	354	—	QJ
2021/06/10	101.92	24.35	8	5.6	100	—	QJ
2021/06/16	101.90	24.34	8	4.8	101	—	QJ
2021/06/28	101.89	24.31	8	4.9	101	—	QJ
2021/11/16	101.68	22.32	10	5.2	213	135	QJ/WN
2021/12/24	101.68	22.34	10	6.6	211	133	QJ/WN
2022/03/05	101.63	22.37	8	4.8	191	131	QJ/WN
2022/07/22	99.90	21.10	10	6.2	434	338	QJ/WN
2022/09/05	102.09	29.59	16	6.8	632	676	QJ/WN
2022/11/19	102.29	23.40	8	5.4	79	42	QJ/WN
2022/11/21	102.27	23.43	14	4.1	—	39	WN
2023/03/03	102.60	22.55	10	4.6	156	129	QJ/WN
2023/03/23	100.69	22.62	10	4.7	—	159	WN
2023/05/31	102.65	24.20	16	4.0	33	108	QJ/WN
2023/08/13	101.86	24.32	10	4.8	104	89	QJ/WN
2023/11/17	99.35	21.20	10	6.2	467	368	QJ/WN

"—" means no data.

Table S2: Model performance metrics (NA, NB, NC, FAR, MAR, POD, TS) under varying parameters p1 and p3 for Na^+ at Qujiang spring.

p1	p3	NB	NA	NA+NC	FAR	MAR	POD	TS
1	1	19	20	22	0.49	**0.09**	**0.91**	0.49
1	1.01	12	18	22	0.40	0.18	0.82	0.53
1	1.02	6	14	22	0.30	0.36	0.64	0.50
1	1.03	5	11	22	0.31	0.50	0.50	0.41

1	1.04	4	9	22	0.31	0.59	0.41	0.35
1	1.05	3	7	22	0.30	0.68	0.32	0.28
1	1.06	2	5	22	0.29	0.77	0.23	0.21
1	1.07	1	4	22	0.20	0.82	0.18	0.17
1	1.08	1	4	22	0.20	0.82	0.18	0.17
1.01	1	14	19	22	0.42	0.14	0.86	0.53
1.01	1.01	8	16	22	0.33	0.27	0.73	0.53
1.01	1.02	5	12	22	0.29	0.45	0.55	0.44
1.01	1.03	5	5	22	0.50	0.77	0.23	0.19
1.01	1.04	4	6	22	0.40	0.73	0.27	0.23
1.01	1.05	1	6	22	**0.14**	0.73	0.27	0.26
1.01	1.06	1	5	22	0.17	0.77	0.23	0.22
1.01	1.07	1	4	22	0.20	0.82	0.18	0.17
1.01	1.08	1	2	22	0.33	0.91	0.09	0.09
1.02	1	8	16	22	0.33	0.27	0.73	0.53
1.02	1.01	4	14	22	0.22	0.36	0.64	**0.54**
1.02	1.02	4	11	22	0.27	0.50	0.50	0.42
1.02	1.03	4	7	22	0.36	0.68	0.32	0.27
1.02	1.04	2	6	22	0.25	0.73	0.27	0.25
1.02	1.05	1	5	22	0.17	0.77	0.23	0.22
1.02	1.06	1	5	22	0.17	0.77	0.23	0.22
1.02	1.07	1	4	22	0.20	0.82	0.18	0.17
1.02	1.08	1	2	22	0.33	0.91	0.09	0.09
1.03	1	4	13	22	0.24	0.41	0.59	0.50
1.03	1.01	4	12	22	0.25	0.45	0.55	0.46
1.03	1.02	2	10	22	0.17	0.55	0.45	0.42
1.03	1.03	2	6	22	0.25	0.73	0.27	0.25
1.03	1.04	2	6	22	0.25	0.73	0.27	0.25
1.03	1.05	1	5	22	0.17	0.77	0.23	0.22
1.03	1.06	1	5	22	0.17	0.77	0.23	0.22
1.03	1.07	1	3	22	0.25	0.86	0.14	0.13
1.03	1.08	1	2	22	0.33	0.91	0.09	0.09
1.04	1	2	10	22	0.17	0.55	0.45	0.42
1.04	1.01	2	8	22	0.20	0.64	0.36	0.33
1.04	1.02	2	7	22	0.22	0.68	0.32	0.29
1.04	1.03	2	6	22	0.25	0.73	0.27	0.25
1.04	1.04	2	5	22	0.29	0.77	0.23	0.21
1.04	1.05	1	5	22	0.17	0.77	0.23	0.22
1.04	1.06	1	5	22	0.17	0.77	0.23	0.22
1.04	1.07	1	3	22	0.25	0.86	0.14	0.13
1.04	1.08	1	2	22	0.33	0.91	0.09	0.09
1.05	1	2	6	22	0.25	0.73	0.27	0.25
1.05	1.01	2	6	22	0.25	0.73	0.27	0.25
1.05	1.02	2	6	22	0.25	0.73	0.27	0.25

1.05	1.03	2	6	22	0.25	0.73	0.27	0.25
1.05	1.04	2	5	22	0.29	0.77	0.23	0.21
1.05	1.05	1	5	22	0.17	0.77	0.23	0.22
1.05	1.06	1	5	22	0.17	0.77	0.23	0.22
1.05	1.07	1	3	22	0.25	0.86	0.14	0.13
1.05	1.08	1	2	22	0.33	0.91	0.09	0.09
1.06	1	2	5	22	0.29	0.77	0.23	0.21
1.06	1.01	2	5	22	0.29	0.77	0.23	0.21
1.06	1.02	2	5	22	0.29	0.77	0.23	0.21
1.06	1.03	2	5	22	0.29	0.77	0.23	0.21
1.06	1.04	2	4	22	0.33	0.82	0.18	0.17
1.06	1.05	1	4	22	0.20	0.82	0.18	0.17
1.06	1.06	1	4	22	0.20	0.82	0.18	0.17
1.06	1.07	1	3	22	0.25	0.86	0.14	0.13
1.06	1.08	1	2	22	0.33	0.91	0.09	0.09

Table S3: Model performance metrics (NA, NB, NC, FAR, MAR, POD, TS) under varying parameters p1 and p3 for SO_4^{2-} at Wana spring.

p1	p3	NB	NA	NA+NC	FAR	MAR	POD	TS
1	1	12	10	12	0.55	**0.17**	**0.83**	0.42
1	1.01	11	10	12	0.52	**0.17**	**0.83**	0.43
1	1.02	11	10	12	0.52	**0.17**	**0.83**	0.43
1	1.03	11	10	12	0.52	**0.17**	**0.83**	0.43
1	1.04	9	8	12	0.53	0.33	0.67	0.38
1	1.05	8	8	12	0.50	0.33	0.67	0.40
1	1.06	7	8	12	0.47	0.33	0.67	0.42
1	1.07	7	6	12	0.54	0.50	0.50	0.32
1	1.08	6	6	12	0.50	0.50	0.50	0.33
1.01	1	11	10	12	0.52	**0.17**	**0.83**	0.43
1.01	1.01	11	10	12	0.52	**0.17**	**0.83**	0.43
1.01	1.02	10	10	12	0.50	**0.17**	**0.83**	0.45
1.01	1.03	10	10	12	0.50	**0.17**	**0.83**	0.45
1.01	1.04	8	8	12	0.50	0.33	0.67	0.40
1.01	1.05	8	8	12	0.50	0.33	0.67	0.40
1.01	1.06	7	8	12	0.47	0.33	0.67	0.42
1.01	1.07	7	6	12	0.54	0.50	0.50	0.32
1.01	1.08	6	6	12	0.50	0.50	0.50	0.33
1.02	1	10	10	12	0.50	**0.17**	**0.83**	0.45
1.02	1.01	10	10	12	0.50	**0.17**	**0.83**	0.45
1.02	1.02	10	10	12	0.50	**0.17**	**0.83**	0.45
1.02	1.03	10	10	12	0.50	**0.17**	**0.83**	0.45
1.02	1.04	8	8	12	0.50	0.33	0.67	0.40

1.02	1.05	8	8	12	0.50	0.33	0.67	0.40
1.02	1.06	7	8	12	0.47	0.33	0.67	0.42
1.02	1.07	7	6	12	0.54	0.50	0.50	0.32
1.02	1.08	6	6	12	0.50	0.50	0.50	0.33
1.03	1	9	10	12	0.47	**0.17**	**0.83**	0.48
1.03	1.01	8	10	12	0.44	**0.17**	**0.83**	0.50
1.03	1.02	7	9	12	0.44	0.25	0.75	0.47
1.03	1.03	7	9	12	0.44	0.25	0.75	0.47
1.03	1.04	7	8	12	0.47	0.33	0.67	0.42
1.03	1.05	7	8	12	0.47	0.33	0.67	0.42
1.03	1.06	6	8	12	0.43	0.33	0.67	0.44
1.03	1.07	6	6	12	0.50	0.50	0.50	0.33
1.03	1.08	5	6	12	0.45	0.50	0.50	0.35
1.04	1	9	10	12	0.47	**0.17**	**0.83**	0.48
1.04	1.01	7	10	12	**0.41**	**0.17**	**0.83**	**0.53**
1.04	1.02	7	9	12	0.44	0.25	0.75	0.47
1.04	1.03	7	9	12	0.44	0.25	0.75	0.47
1.04	1.04	7	8	12	0.47	0.33	0.67	0.42
1.04	1.05	7	8	12	0.47	0.33	0.67	0.42
1.04	1.06	6	8	12	0.43	0.33	0.67	0.44
1.04	1.07	6	6	12	0.50	0.50	0.50	0.33
1.04	1.08	5	6	12	0.45	0.50	0.50	0.35
1.05	1	9	9	12	0.50	0.25	0.75	0.43
1.05	1.01	8	9	12	0.47	0.25	0.75	0.45
1.05	1.02	8	9	12	0.47	0.25	0.75	0.45
1.05	1.03	7	9	12	0.44	0.25	0.75	0.47
1.05	1.04	7	8	12	0.47	0.33	0.67	0.42
1.05	1.05	7	8	12	0.47	0.33	0.67	0.42
1.05	1.06	6	8	12	0.43	0.33	0.67	0.44
1.05	1.07	6	6	12	0.50	0.50	0.50	0.33
1.05	1.08	5	6	12	0.45	0.50	0.50	0.35
1.06	1	7	8	12	0.47	0.33	0.67	0.42
1.06	1.01	7	8	12	0.47	0.33	0.67	0.42
1.06	1.02	6	7	12	0.46	0.42	0.58	0.39
1.06	1.03	6	7	12	0.46	0.42	0.58	0.39
1.06	1.04	6	6	12	0.50	0.50	0.50	0.33
1.06	1.05	6	6	12	0.50	0.50	0.50	0.33
1.06	1.06	5	6	12	0.45	0.50	0.50	0.35
1.06	1.07	5	5	12	0.50	0.58	0.42	0.29
1.06	1.08	4	5	12	0.44	0.58	0.42	0.31

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Table S4: Parameters of anomaly detection models for each hydrochemical component.

Parameter	Na^+	K^+	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	F^-	δD	$\delta^{18}O$	Sites
p1	1.02	1.05	1.04	1.04	1.01	1.01	1.06	0.994	0.989	QJ
p3	1.01	1.01	1.04	1.02	1.02	1.02	1.01	0.997	0.997	
p1	1.04	1.07	1.06	1.02	1.04	1.06	1.02	1.001	1.001	WN
p3	1.02	1.04	1.01	1.03	1.01	1.02	1.01	1.002	1.002	
p2	18									QJ/WN
p4	1.5									
p5	1.6									
T_{th}	45									

Table S5: Model performance comparison across different numbers of synchronous anomalous components.

Components (N)	Qujiang spring				Wana spring			
	POD	FAR	MAR	TS	POD	FAR	MAR	TS
N ≥ 2	1	0.37	0	0.63	1.00	0.43	0	0.57
N ≥ 3	0.95	0.27	0.05	0.70	0.83	0.33	0.17	0.59
N ≥ 4	0.77	0.29	0.23	0.59	0.75	0.31	0.25	0.56
N ≥ 5	0.55	0.29	0.45	0.44	0.67	0.20	0.33	0.57
N ≥ 6	0.36	0.11	0.64	0.35	0.58	0.13	0.42	0.54

Table S6: Model performance evaluation and uncertainty analysis of hydrochemical components at Qujiang and Wana springs based on 1,000 bootstrap resamples.

Comp -onent	Qujiang spring			Wana spring		
	POD (95% CI)	FAR (95% CI)	TS (95% CI)	POD (95% CI)	FAR (95% CI)	TS (95% CI)
Na^+	0.64 (0.43, 0.83)	0.22 (0.05, 0.44)	0.54 (0.35, 0.73)	0.42 (0.17, 0.67)	0.00 (0.00, 0.00)	0.42 (0.17, 0.67)

K^+	0.55 (0.35, 0.74)	0.37 (0.18, 0.61)	0.41(0.23, 0.57)	0.50 (0.22, 0.79)	0.33 (0.07, 0.67)	0.40 (0.13, 0.67)
Ca^{2+}	0.73 (0.54, 0.91)	0.36 (0.19, 0.60)	0.52 (0.31, 0.69)	0.75 (0.50, 1.00)	0.36 (0.14, 0.63)	0.53 (0.29, 0.76)
Cl^-	0.77 (0.58, 0.95)	0.37 (0.21, 0.58)	0.53 (0.33, 0.70)	0.75 (0.50, 1.00)	0.36 (0.12, 0.60)	0.53 (0.29, 0.76)
SO_4^{2-}	0.59 (0.38, 0.79)	0.28 (0.10, 0.50)	0.48 (0.30, 0.67)	0.83 (0.58, 1.00)	0.41 (0.13, 0.62)	0.53 (0.33, 0.78)
HCO_3^-	0.41 (0.21, 0.62)	0.44 (0.24, 0.71)	0.31 (0.17, 0.47)	0.58 (0.31, 0.86)	0.22 (0.00, 0.50)	0.50 (0.29, 0.79)
F^-	0.55 (0.35, 0.75)	0.43 (0.13, 0.56)	0.39 (0.25, 0.61)	0.58 (0.30, 0.86)	0.36 (0.09, 0.67)	0.44 (0.19, 0.69)
δD	1.00 (1.00, 1.00)	0.20 (0.00, 0.60)	0.80 (0.40, 1.00)	1.00 (1.00, 1.00)	0.50 (0.20, 0.80)	0.50 (0.20, 0.80)
$\delta^{18}O$	0.75 (0.25, 1.00)	0.40 (0.00, 0.83)	0.50 (0.17, 0.83)	1.00 (1.00, 1.00)	0.44 (0.11, 0.78)	0.56 (0.22, 0.89)
DA	0.95 (0.85, 1.00)	0.28 (0.10, 0.45)	0.70 (0.53, 0.87)	0.83 (0.60, 1.00)	0.33 (0.12, 0.60)	0.59 (0.35, 0.82)

Note: Values are original estimated metrics; values in parentheses are their corresponding 95% confidence intervals (CI).

Table S7: Statistical analysis of anomalous variations in hydrochemical components.

Component	Qujiang spring				Wana spring			
	Increase (*n*)	Decrease (*n*)	Increase Ratio	Decrease Ratio	Increase (*n*)	Decrease (*n*)	Increase Ratio	Decrease Ratio
Na^+	10	4	0.71	0.29	3	1	0.75	0.25
K^+	8	4	0.67	0.33	3	2	0.60	0.40
Ca^{2+}	10	6	0.63	0.38	4	5	0.44	0.56
Cl^-	11	7	0.61	0.39	6	3	0.67	0.33
SO_4^{2-}	10	3	0.77	0.23	5	5	0.50	0.50
HCO_3^-	6	4	0.60	0.40	5	2	0.71	0.29
F^-	11	4	0.73	0.27	4	3	0.57	0.43
δD	1	3	0.25	0.75	2	3	0.40	0.60
$\delta^{18}O$	1	2	0.33	0.67	2	3	0.40	0.60

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