

Supplementary Material

Table S1. Sensitivity of drought recovery timing to threshold selection. Recovery month is expressed as months elapsed since the September 2022 drought peak. Meteorological variables (precipitation, SPEI-6) use first sustained recovery (≥ 2 consecutive months above threshold); hydrological variables (river discharge, SMSA, GWSA) use final stable recovery (Van Loon et al., 2016). Thresholds tested are one level stricter and one level more lenient than the baseline values reported in Section 3.5. "N/A" indicates that recovery was not confirmed within the available record (December 2023 for discharge and soil moisture; December 2024 for GWSA).

Variable	Recovery type	Strict threshold	Strict recovery (month)	Strict (months after peak)	Baseline threshold	Baseline recovery (month)	Baseline (months after peak)	Lenient threshold	Lenient recovery (month)	Lenient (months after peak)
Precipitation anomaly	First sustained	-20mm	2022-09	0	0mm (base)	2023-05	8	+10mm	2023-06	9.0
SPEI-6	First sustained	-1.0	2023-05	8	-0.5 (base)	2023-05	8	0.0	2023-08	11.0
River discharge (Q)	First sustained	Q25	2023-05	8	Q50 (base)	2023-11	14	Q75	N/A	N/A
SMSA	Final stable	-20mm	2023-05	8	-10mm (base)	2023-05	8	0mm	N/A	N/A
GWSA	Final stable	-100mm	2024-01	16	-50mm (base)	2024-02	17	0mm	N/A	N/A

Note. Strict threshold = one step stricter than baseline; Lenient threshold = one step more lenient. "N/A" = recovery not confirmed within available record. SMSA = soil moisture storage anomaly; GWSA = groundwater storage anomaly; SPEI = Standardised Precipitation–Evapotranspiration Index.

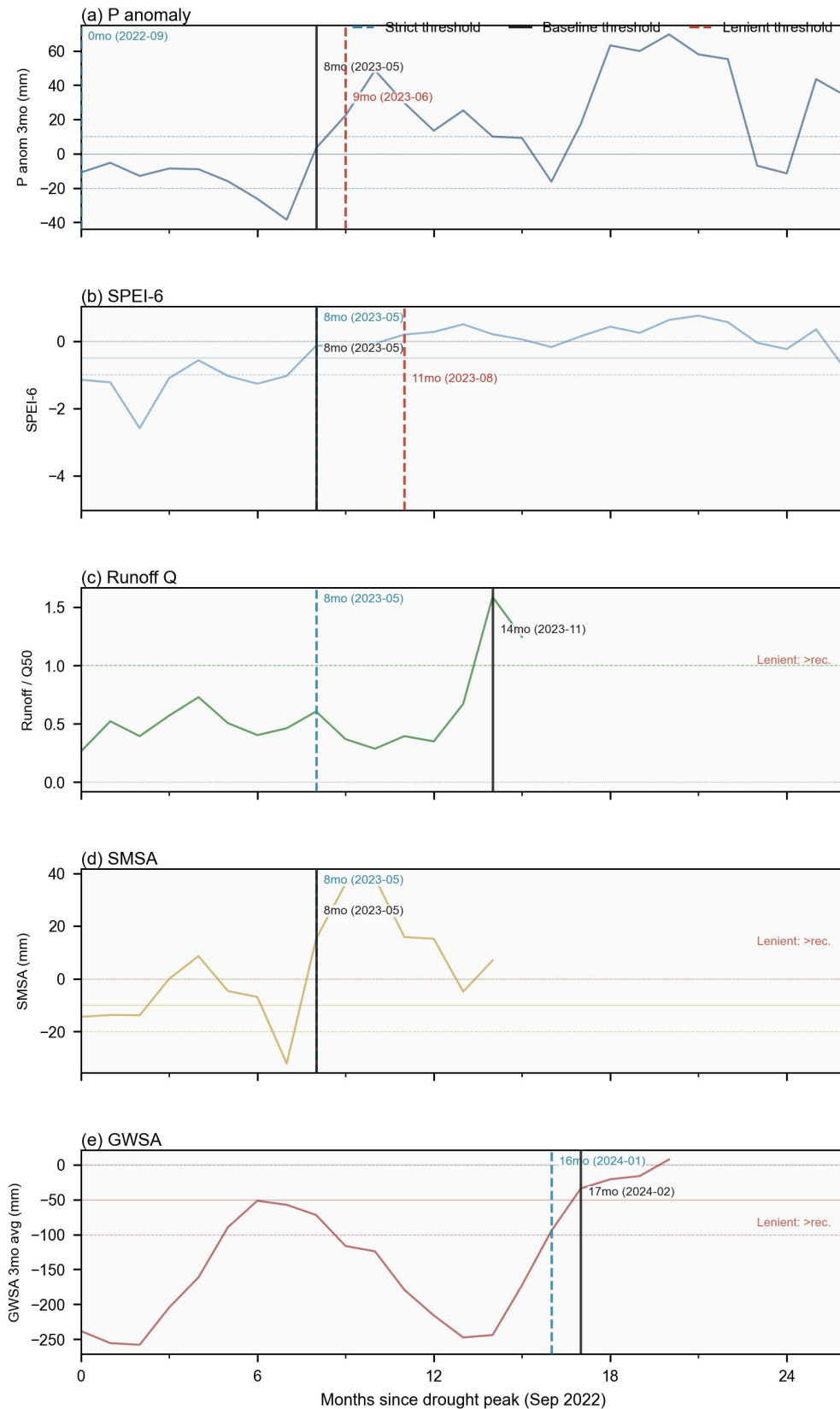


Figure S1. Sensitivity of drought recovery timing to threshold selection for five hydroclimatic variables at Pontelagoscuro. For each variable, the recovery month is shown under a strict threshold (blue dashed line), the baseline threshold (black solid line), and a lenient threshold (red dashed line), expressed as months since the September 2022 drought peak. Values not reached within the record are indicated by a rightward arrow. SPEI-6

recovery is robust (8–11 months across all thresholds). River discharge recovery is more sensitive (8–14 months). GWSA recovery consistently falls in the third tier (16–17 months under the fixed –50 mm threshold); recovery against the calendar-month 20th percentile was not reached within the observational record.

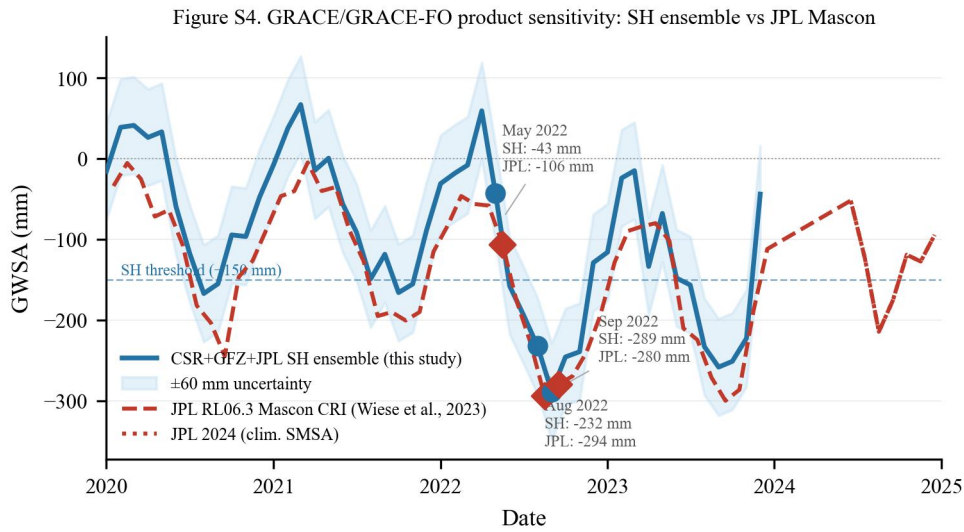


Figure S2. Comparison of monthly GWSA derived from the three-centre spherical harmonic ensemble (blue solid line; NASA/GRACE/MASCON GRIDS/LAND via Google Earth Engine; Landerer et al., 2020) and the JPL RL06.3 Mascon CRI solution (red dashed line; Wiese et al., 2023) for the Po Basin, 2020–2024. Grey shading indicates the ± 60 mm (95 % CI) uncertainty envelope on the ensemble product. Both products use ERA5-Land (three-layer, 0–100 cm) soil moisture and snow water equivalent for GWSA isolation, relative to the 2004–2009 baseline. Key differences: (1) timing of the 2022 GWSA minimum (ensemble: September, –289 mm; JPL: August, –294 mm); (2) May 2022 pre-irrigation baseline (ensemble: –43 mm; JPL: –106 mm), which drives the difference in irrigation-season depletion magnitude (Section 5.6). ERA5-Land SMSA data end December 2023 for the ensemble product; the 2024 JPL extension uses climatological SMSA and carries an additional uncertainty of ± 30 mm.

Supplementary Methods

S1 Drought recovery threshold sensitivity

Recovery timing in Section 3.5 was re-evaluated at thresholds one step stricter and one step more lenient than the baseline for each variable. Baseline thresholds follow Herbert et al. (2025): SPEI-6 > -1.0 (strict: -0.5 ; lenient: -1.5), river discharge above the 20th percentile (strict: 30th; lenient: 10th), SMSA > -10 mm (strict: -5 mm; lenient: -20 mm), and GWSA above the calendar-month 20th percentile (strict: 30th; lenient: 10th), as well as GWSA against a fixed -50 mm threshold. Results are in Table S1 and Figure S3.

S2 GWSA product comparison

GWSA was derived from two GRACE-FO products: the three-centre spherical harmonic ensemble (CSR/GFZ/JPL; Landerer et al., 2020) and the JPL RL06.3 Mascon CRI solution (Wiese et al., 2023). Both were masked to the Po Basin boundary, gap-filled with climatological means (≤ 3 gaps per product over 2020–2024), and converted to equivalent water height anomalies relative to the 2004–2009 baseline (Rodell et al., 2018). ERA5-Land SMSA and SWEA were subtracted identically from both to isolate GWSA. Figure S4 shows the resulting time series and sources of divergence between products.