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From Meteorological Recovery to Soil-Water Persistence: A Native-Grid Multiscale Drought Framework for the Ionian Islands, Greece (1981–2024) †

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Abstract

Drought monitoring on small islands is challenged by coastline-grid mismatch and by the possibility that meteorological recovery precedes recovery of soil-water conditions. This study presents a native-grid, area-weighted framework for the Ionian Islands using Climate Hazards Center Infrared Precipitation with Stations version 3 (CHIRPS v3), TerraClimate potential evapotranspiration, and modelled soil-water storage for 1981–2024. The framework preserves each product's original spatial support, derives monthly island series, calculates the Standardized Precipitation Evapotranspiration Index (SPEI) at 1-, 3-, 6-, and 12-month scales, constructs a drought-event catalogue, evaluates temporal trends, and quantifies soil-water recovery. It identified 690 scale-specific events; longer accumulation scales produced fewer but more persistent events. No generalized robust intensification was detected. Full-period negative SPEI-3 signals in Kefalonia and Ithaca were sensitive to the 2020–2024 terminal period, while the remaining island trends were not significant after false discovery rate adjustment. In 34.3% of completed events, modelled soil-water storage remained below normal when SPEI first returned to nonnegative values. Recovery lags had a median of 0 months, a 90th percentile of 4 months, and a maximum of 20 months. The framework provides a transparent, transferable basis for drought monitoring and water-resource planning in insular environments.

Keywords: drought monitoring; standardized precipitation evapotranspiration index; CHIRPS; TerraClimate; soil-water storage; Ionian Islands; water resource management; geoinformatics

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1. Introduction

Drought is a recurrent hydroclimatic hazard whose interpretation depends on the variable and time scale used [1]. The Standardized Precipitation Evapotranspiration Index (SPEI) combines precipitation and atmospheric evaporative demand across multiple accumulation windows [2,3]. This property is important in Mediterranean environments, where short seasonal deficits and persistent water-balance anomalies coexist and where warming has increased drought pressure in parts of southern Europe [4,5].

Small islands pose a specific monitoring challenge because limited land area, irregular coastlines, topographic gradients, and sparse station networks make simple grid-cell averages sensitive to land–sea mixing. Existing regional assessments often aggregate gridded variables over common analysis grids, potentially obscuring the original spatial support of coastal products. Recent Greek-island research has shown the value of combining standardized drought indices with soil-water information [6], while drought-propagation studies indicate that meteorological normalization may precede soil-water recovery [7], a distinction also recognized in operational European monitoring systems [8].

The need addressed here is therefore not another drought index, but a transparent way to connect coastal spatial support, multiscale events, robust trend inference, and recovery information at island scale. This study develops such a framework for Zakynthos, Kefalonia, Lefkada, Kerkyra, and Ithaca. It (i) aggregates climate variables on their original grids using exact cell-island intersection areas, (ii) converts SPEI-1/3/6/12 into a censor-aware event catalogue, (iii) evaluates trends with serial-correlation correction, false discovery rate control, and terminal-period sensitivity, and (iv) links meteorological recovery to modelled soil-water persistence. The main objective is a reproducible small-island monitoring workflow that can be transferred to other insular environments when comparable data are available.

2. Materials and Methods

The framework, applied to the Ionian Islands (Figure 1), comprises five connected stages (Figure 2). First, precipitation, potential evapotranspiration, and soil-water storage are retained on the original grid of each source product. Second, exact cell-island overlap areas are used to derive consistent monthly island series. Third, the climatic water balance is standardized at four accumulation scales to represent short-term, seasonal, intermediate, and persistent conditions. Fourth, continuous negative runs are converted into a right-censoring-aware event catalogue. Finally, temporal trends and post-event soil-water recovery are evaluated. These stages were selected to address two central challenges of insular drought monitoring: coastal grid mismatch and the persistence of soil-water deficits after meteorological conditions have normalized.

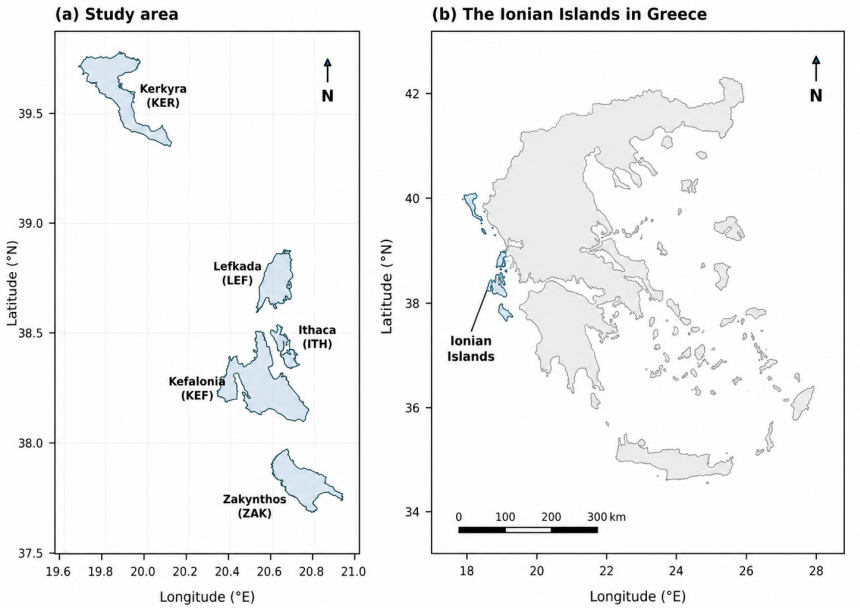


Figure 1. (**a**) The Ionian Islands analyzed in this study, based on the authoritative study boundaries; (**b**) their location within Greece.

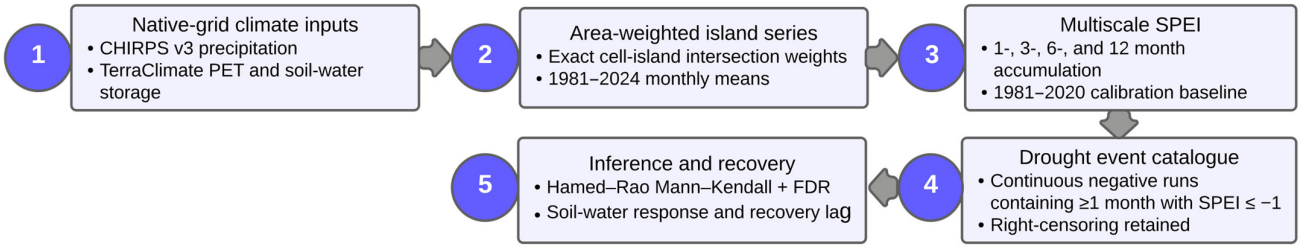


Figure 2. Analytical workflow linking native-grid climate inputs, multiscale SPEI, drought-event construction, trend inference, and soil-water recovery analysis. Abbreviations: CHIRPS v3, Climate Hazards Center Infrared Precipitation with Stations version 3; PET, potential evapotranspiration; SPEI, Standardized Precipitation Evapotranspiration Index; FDR, false discovery rate.

2.1. Study Area, Data, and Native-Grid Aggregation

The study area comprises the Ionian Islands in western Greece (Figure 1). January 1981–December 2024 provided 528 months per island and 2640 island-month records. Climate Hazards Center Infrared Precipitation with Stations version 3 (CHIRPS v3) pentadal precipitation at 0.05° was aggregated from exactly six valid pentads per month [9]. TerraClimate supplied monthly potential evapotranspiration (PET) and modelled soil-water storage at 1/24°; both were converted to millimetres using the official 0.1 scale factor [10].

In this study, native grid denotes the original cell geometry, spatial resolution, and alignment supplied by each data product before any resampling, interpolation, or reprojection to a common analysis grid. Spatial support was fixed for the full record. Every native cell intersecting a detailed island boundary was retained, and its exact cell-island intersection area was used as the weight in the monthly island mean. The support contained 178 CHIRPS and 212 TerraClimate cells. No interpolation, resampling, focal filling, or synthetic completion was applied; this procedure reduces coastal land–sea mixing without implying finer spatial information than the source products provide.

2.2. SPEI Calculation and Drought-Event Definition

For each island and month, the climatic water balance was calculated as $D = P - PET$, where P is monthly precipitation, PET is monthly potential evapotranspiration, and D is expressed in millimetres. D was accumulated over unshifted trailing windows of 1, 3, 6, and 12 months. SPEI-1 represents monthly anomalies, SPEI-3 short seasonal conditions, SPEI-6 intermediate accumulated deficits, and SPEI-12 more persistent annual-scale conditions. For each island, scale, and calendar month, the generalized logistic (log-logistic) distribution was fitted to the fixed 1981–2020 calibration baseline using unbiased probability-weighted moments and L-moments [3,11]; cumulative probabilities were then transformed to standard-normal SPEI values. The fixed baseline ensured that values through 2024 were evaluated against the same reference distribution. Initial $k - 1$ windows were retained as missing rather than zero-filled.

Moderate, severe, and extreme drought thresholds were SPEI ≤ -1, ≤ -1.5, and ≤ -2. A primary event began when SPEI became negative, continued while it remained negative, and was retained only if it contained at least one month with SPEI ≤ -1; it ended before the first SPEI ≥ 0 month. Events active in December 2024 were right-censored and excluded from duration or recovery analyses requiring a known endpoint.

2.3. Trend Inference and Soil-Water Recovery

Trend diagnostics were conducted for all four SPEI scales across prespecified annual and seasonal metrics. Annual and seasonal series were analysed with the Hamed–Rao variance-corrected Mann–Kendall test [12] and Theil–Sen slopes [13]. Benjamini–Hochberg

adjustment controlled the false discovery rate (FDR) at $q \leq 0.05$ [14]. FDR is the expected proportion of false-positive findings among the results declared significant; q-values are *p*-values adjusted for multiple testing, and $q \leq 0.05$ was the significance criterion. Full-period results (1981–2024) were repeated for 1981–2019 to identify dependence on the 2020–2024 terminal segment; Pettitt tests were exploratory only [15].

TerraClimate soil-water storage was standardized independently by island and calendar month against 1981–2020. Meteorological recovery was the first SPEI ≥ 0 month after an event, and soil-water recovery was the first $z \geq 0$ month on or after that date; their difference defined the recovery lag. The variable is modelled storage in millimetres, not direct volumetric soil moisture.

3. Results

The framework generated five linked output groups: (i) a quality-controlled dataset of 2640 island-month records; (ii) four monthly SPEI series for each island; (iii) a catalogue of 690 scale-specific drought events; (iv) 140 annual and 240 seasonal trend diagnostics with multiple-testing control; and (v) event-level indicators of soil-water response and recovery. The following sections present these outputs in the sequence of the analytical workflow, from multiscale event structure to temporal inference and soil-water persistence.

3.1. Hydroclimatic Context and Scale-Dependent Event Structure

The islands shared a wet-winter/dry-summer cycle but differed in mean annual water balance: Kerkyra had the highest precipitation (1209.9 mm) and a slightly positive balance (+84.3 mm), whereas Zakynthos had the lowest precipitation (851.4 mm) and the most negative balance (−330.5 mm). The catalogue contained 690 scale-specific events: 326 at SPEI-1, 191 at SPEI-3, 123 at SPEI-6, and 50 at SPEI-12. Of these, 674 were completed and 16 right-censored. Mean completed-event duration increased from 2.75 to 19.42 months and cross-year events from 12.6% to 92.0% as scale lengthened (Figure 3; Table 1). Event-active months ranged from 31.2% to 42.6% among island-scale combinations.

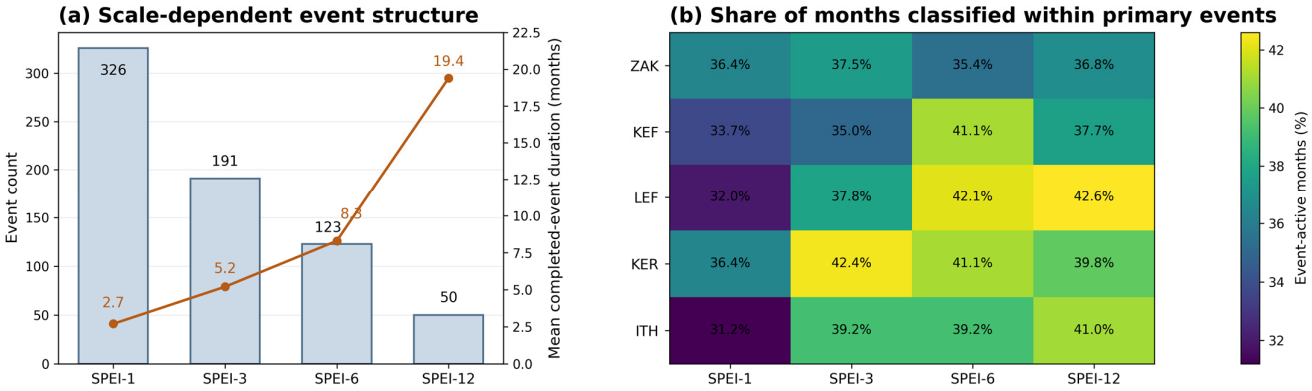


Figure 3. (**a**) Number of primary drought events and mean duration of completed events by SPEI scale; (**b**) event-active-month synthesis showing the percentage of valid months within primary events for each island and scale.

3.2. Temporal Trends and Sensitivity to the Recent Period

Across the 140 annual and 240 seasonal diagnostics conducted for the four SPEI scales, only two full-period results remained significant after FDR adjustment; both concerned annual minimum SPEI-3. Kefalonia (−0.122 per decade) and Ithaca (−0.146 per decade) were significant for 1981–2024 ($q = 0.0347$ for both), but significance disappeared for 1981–2019 ($q = 0.3688$ and 0.6072), so both signals were classified as recent-period-sensitive rather

than persistent (Figure 4). For direct comparison, the corresponding annual minimum SPEI-3 results for Kerkyra (−0.016), Lefkada (−0.143), and Zakynthos (−0.156) are also presented; none was significant after FDR adjustment (Figure 5). Zakynthos had the steepest numerical slope (q = 0.0850), illustrating the distinction between effect size and statistical support. No seasonal trend passed FDR correction.

Table 1. Main scale-specific drought-event and soil-recovery results.

Scale	Events	Complete/ Censored	Mean Duration (Months)	Severe/ Extreme (%)	Cross-Year (%)	Below-Normal Storage at Recovery (%)	P90 Lag (Months)
SPEI-1	326	325/1	2.75	38.3	12.6	38.2	5
SPEI-3	191	186/5	5.22	52.4	30.9	36.6	4
SPEI-6	123	118/5	8.31	55.3	61.8	28.0	4
SPEI-12	50	45/5	19.42	60.0	92.0	13.3	1

P90 lag: 90th percentile of the soil-water recovery lag after the first nonnegative SPEI month. Percentages use scale-specific eligible events.

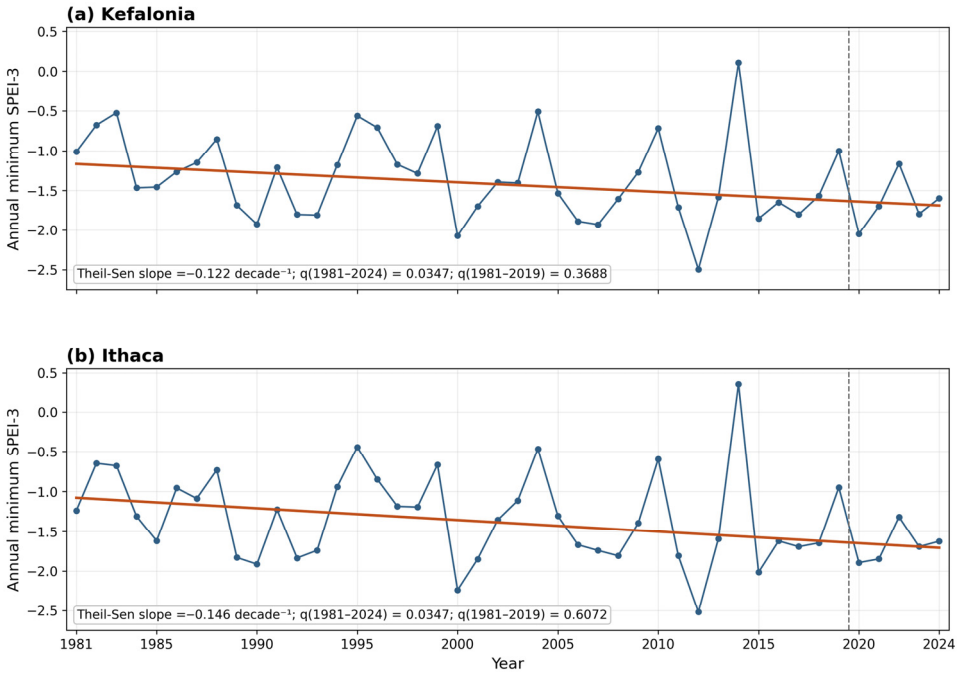


Figure 4. Annual minimum SPEI-3 in (**a**) Kefalonia and (**b**) Ithaca. Blue points connected by lines show annual minimum SPEI-3; orange lines show full-period Theil–Sen trends (1981–2024). The vertical dashed line separates 1981–2019 from the 2020–2024 terminal period used in the sensitivity analysis.

3.3. Soil-Water Response and Recovery Persistence

SPEI and modelled soil-water storage were mainly synchronous or formed broad near-zero-lag plateaus. Among 674 completed events, 231 (34.3%) still had below-normal storage at the first nonnegative SPEI month. The median recovery lag was 0 months, the 90th percentile 4 months, and the maximum 20 months. Persistence varied by island and scale (Figure 6). Although below-normal storage at recovery declined from 38.2% at SPEI-1 to 13.3% at SPEI-12, the median minimum event z became more negative (−0.74 to −1.80), indicating that later meteorological recovery at long scales should not be interpreted as a weaker soil-water response.

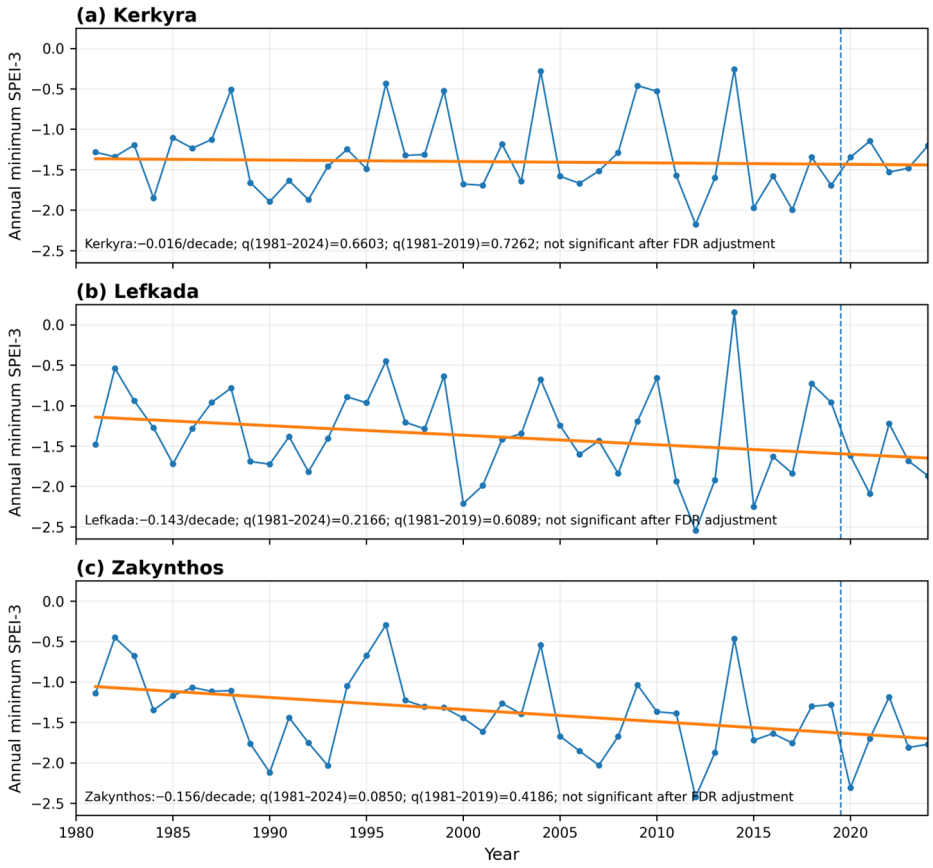


Figure 5. Annual minimum SPEI-3 in (**a**) Kerkyra, (**b**) Lefkada, and (**c**) Zakynthos. Blue points connected by lines show annual minimum SPEI-3; orange lines show full-period Theil–Sen trends (1981–2024). The vertical dashed line separates 1981–2019 from the 2020–2024 terminal period used in the sensitivity analysis. None of the three full-period trends was significant after FDR adjustment.

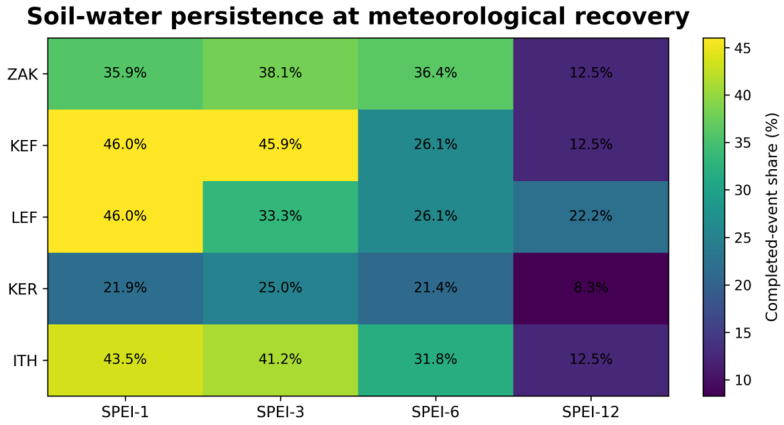


Figure 6. Island-by-scale synthesis of completed events retaining below-normal modelled soil-water storage at the first nonnegative SPEI month.

4. Discussion

The main methodological strength of the framework is the integration of spatial-support control, multiscale event characterization, robust trend inference, and soil-water recovery within one reproducible sequence. Retaining native grids avoids implying spatial detail that is absent from the source products, while exact intersection weighting limits the influence of mixed coastal cells. The event-based structure complements monthly

index summaries by making event duration, severity, censoring, and recovery explicit. The case study also confirms that small-island drought is scale dependent: short windows resolve frequent, brief anomalies, whereas long windows merge deficits into fewer, more persistent events.

Trend inference required caution. Negative annual-minimum SPEI-3 slopes did not constitute uniform evidence of intensification: only two tests survived FDR adjustment and both depended on the final five years (Figure 4), whereas the remaining three island trends were not significant after FDR adjustment (Figure 5). Regional evidence of increasing European and southern-European drought pressure [4,5] therefore cannot be assumed to appear as a stable local monotonic trend in every island metric.

The clearest operational implication is that a nonnegative SPEI does not guarantee simultaneous recovery of modelled soil-water storage. The 34.3% persistence rate and long upper tail of lags are consistent with drought-propagation research [7] and with monitoring systems that retain recovery states [8]. The framework can therefore support the timing of additional island-scale checks, but it cannot estimate reservoir volume, groundwater levels, water demand, or irrigation restrictions.

The workflow is transferable to other insular environments because it requires only accurate island boundaries and temporally consistent precipitation, evapotranspiration, and soil-water inputs. Transfer nevertheless requires locally justified calibration and interpretation. Monthly island means omit within-island catchments; TerraClimate storage is modelled; SPEI remains source-sensitive; 16 events were right-censored; and correlations and lags are descriptive rather than causal. Local station or field validation and catchment-scale analysis would therefore strengthen future applications.

5. Conclusions

This study contributes a transparent and reproducible framework for converting gridded hydroclimatic data into multiscale, event-based drought information for small islands. Its methodological contribution lies in combining native-grid area weighting, four SPEI accumulation scales, censor-aware event construction, robust trend inference, and soil-water recovery analysis rather than in proposing a new drought index. Applied to the Ionian Islands for 1981–2024, the framework identified 690 scale-specific events; longer accumulation scales produced fewer, longer, and more frequently cross-year episodes. No generalized robust monotonic intensification was established. Full-period annual-minimum SPEI-3 declines in Kefalonia and Ithaca were sensitive to the 2020–2024 terminal period, while the corresponding trends for the other islands were not significant after FDR adjustment. Meteorological and soil-water recovery coincided in most events, but 34.3% retained below-normal modelled storage at the first nonnegative SPEI month and rare lags reached 20 months. The workflow can support comparable drought assessments in other insular environments, provided that spatial support, data quality, calibration choices, and hydrological limitations are explicitly considered.

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Conflicts of Interest: G.S. is the co-owner/co-founder of Systems Dynamics. The company had no role in the study design, data acquisition, analysis, interpretation of results, manuscript preparation, funding, or decision to submit the paper. The remaining authors declare no conflicts of interest.

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