From basin-scale variability to regional coherence: emergence of a dominant common mode in reservoir storage dynamics in Catalonia

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Abstract. Long-term records of reservoir storage provide an integrated observational view of regional hydrological variability in managed systems and are directly relevant for water-resource management and drought risk assessment at regional scale. Here we analyze daily records of stored water volume percentages for major reservoirs in Catalonia over the period 1960–2026, using exclusively observational data provided by the Catalan Water Agency. After physically consistent preprocessing, we construct a set of annual metrics, including the annual mean stored volume percentage and the fraction of days below defined low-storage thresholds. Pairwise correlation analyses reveal a clear contrast between intra-basin and inter-basin behavior and show a pronounced increase in inter-basin synchronization after the late 1980s, particularly for low-storage and extreme drought metrics that are most relevant for water scarcity conditions. To assess whether this increased synchronization reflects emergent inter-basin coupling or the dominance of a common empirical mode of co-variability, we explicitly remove the leading mode of co-variability using a principal-component-based common-mode analysis applied to the annual reservoir metrics. After removal of this dominant mode, inter-basin correlations are strongly reduced in both early and late periods, and the apparent pre/post contrast is substantially weakened. The analysis provides robust observational evidence that inter-basin correlations strengthen after the late 1980s and that this change is largely captured by a single dominant empirical mode of co-variability (PC1) in the annual reservoir metrics. Residual inter-basin structure beyond this leading mode is comparatively weaker and does not exhibit the same systematic pre/post amplification. These results indicate that reservoir systems that were historically only weakly coordinated now behave increasingly as a single regional system dominated by a common empirical mode of co-variability, particularly during drought-relevant conditions. This has direct implications for water management, as it limits the effectiveness of spatial diversification and inter-basin compensation strategies. No causal attribution is attempted; the results instead provide a quantitative observational baseline for future studies combining reservoir data with climatic and operational covariates.

1 Introduction

Reservoir systems play a central role in water-resource management in regions characterized by strong interannual hydroclimatic variability and high societal demand (Vörösmarty et al., 2000). Beyond their operational function, long-term records of reservoir storage provide an integrated observational description of the hydrological state of a region, reflecting the combined effects of precipitation, runoff generation, basin-scale hydrology, and water management practices and therefore constitute a directly observable quantity linking climatic variability to management-relevant system response.

Most analyses of drought and water scarcity focus either on meteorological variables, such as precipitation or temperature, or on individual basins considered in isolation (Van Loon, 2015; Stahl et al., 2010). While these approaches are essential for understanding local processes, they do not directly address how hydrological stress is organized in space across multiple basins. In particular, they provide limited insight into whether low-storage conditions arise independently in different systems or whether they evolve coherently at the regional scale (Hannaford et al., 2011; Giuntoli et al., 2013), which is a key aspect for understanding system-wide drought risk.

The distinction between local and regional behavior is not merely conceptual. If hydrological stress remains largely asynchronous across basins, spatial diversification and inter-basin compensation strategies can mitigate risk (Hashimoto et al., 1982; Labadie, 2004). Conversely, if multiple basins experience low-storage conditions simultaneously, water scarcity becomes a genuinely regional phenomenon, reducing the effectiveness of such strategies and increasing systemic vulnerability (Pokhrel et al., 2021), as alternative sources of water are simultaneously constrained.

Detecting regional coherence in managed hydrological systems is not straightforward. Reservoir storage is influenced by both external climatic forcing and internal factors such as basin characteristics, infrastructure, and operational decisions. Apparent synchronization between reservoirs may therefore arise either from genuine coupling between systems or from the imprint of a dominant empirical mode of co-variability acting simultaneously on otherwise independent basins. Disentangling these possibilities requires analyses that explicitly separate shared variability from basin-specific behavior and quantify the relative importance of these contributions over time.

Catalonia offers a particularly suitable setting for this type of investigation. Its reservoir network spans multiple river basins with distinct hydrological characteristics, some of which are hydraulically or operationally linked, while others remain largely independent. At the same time, all basins are embedded within the same broader regional climate (Lionello, 2012; Vicente-Serrano et al., 2014), providing a natural laboratory to examine the emergence of large-scale coherence in reservoir storage dynamics under shared external forcing but heterogeneous local conditions.

In this work, we analyze more than six decades of daily records of stored water volume percentages for the main reservoirs in Catalonia. The objectives are threefold. First, we characterize long-term reservoir storage dynamics using physically motivated preprocessing and robust annual metrics. Second, we quantify the degree of synchronization between reservoirs within and across basins and examine how this structure evolves over time. Third, we assess whether the observed increase in inter-basin synchronization reflects emergent coupling between systems or can be explained by the dominance of a common empirical mode of co-variability across basins.

The analysis is strictly observational and does not rely on external meteorological or climatic datasets. Rather than attempting causal attribution, the focus is on establishing a clear and internally consistent statistical description of the collective behavior of reservoir systems. This approach provides a necessary foundation for subsequent studies aimed at identifying the physical or operational drivers underlying regional-scale hydrological coherence and for informing the interpretation of drought risk at the scale relevant for water management.

Table 1. Reservoirs included in the analysis, together with basin affiliation and approximate temporal coverage of the available ACA daily records.

Reservoir	Basin	Period of record
Darnius Boadella	Muga	1971–2026
Foix	Foix	1960–2026
Riudecanyes	Riudecanyes	1961–2026
Sant Ponç	Llobregat	1961–2026
Sau	Ter	1964–2026
Siurana	Ebre	1972–2026
Susqueda	Ter	1967–2026
La Baells	Llobregat	1977–2026
La Llosa del Cavall	Llobregat	1998–2026
Gaià	Gaià	1995–2026

2 Data

The analysis is based on historical records of reservoir storage provided by the Catalan Water Agency (Agència Catalana de l'Aigua, ACA). The dataset consists of daily observations of the percentage of stored water volume for the main reservoirs in Catalonia, covering the period from 1960 to 2026.

The original data were obtained from two ACA compilations. The first dataset spans the period 1960–2007, while the second covers 2007–2026. Both datasets share a common structure and variable definition. They were merged into a single continuous time series, and duplicated records in the overlapping year (2007) were identified and removed, retaining a single daily value per reservoir.

Each record includes the observation date, the reservoir name, the associated river basin (*conca*), and the percentage of stored water volume relative to the nominal capacity of the reservoir. Only observations corresponding to the variable "Percentatge volum embassat" and expressed in percentage units were retained for the analysis.

The study focuses on ten reservoirs for which long-term daily storage-percentage records are available in the ACA compilations, providing coverage across several river basins in Catalonia. Basin affiliation is used explicitly to distinguish between reservoirs that are potentially hydrologically or operationally coupled and those that belong to independent systems. The temporal coverage is not identical for all reservoirs, and subsequent analyses account for data availability by restricting pairwise comparisons to years with sufficient temporal overlap.

A summary of the analyzed reservoirs, basin affiliation, and approximate temporal coverage is provided in Table 1.

The temporal resolution of the dataset is daily. Daily values are used for data validation and physical consistency checks, while the core analysis is performed on derived annual metrics. This aggregation suppresses short-term operational variability and emphasizes interannual and multi-decadal behavior, which are the primary focus of the present study.

No external hydrological, meteorological, or climatic datasets are used. The analysis relies exclusively on the observational reservoir storage records described above, ensuring that all results reflect the internal dynamics of the managed hydrological system as captured by the evolution of stored water volume percentages.

3 Preprocessing

The daily reservoir records were subjected to a minimal preprocessing procedure aimed exclusively at ensuring physical consistency, while preserving the intrinsic hydrological and operational variability of the system. No statistical smoothing, detrending, normalization, or temporal filtering was applied.

Reservoir storage is constrained by physical and operational limits and cannot change arbitrarily fast. Extremely large variations in stored water percentage over very short time intervals are therefore indicative of measurement errors, reporting inconsistencies, or data handling artefacts rather than genuine hydrological processes. To account for this, a physically motivated consistency check was applied independently to each reservoir time series.

For each reservoir, successive daily observations were compared, and changes exceeding a maximum admissible rate of variation were flagged as non-physical. The threshold was defined as a maximum change of 4 percentage points per day, scaled linearly with the time gap between consecutive observations. This criterion allows for rapid but realistic variations during intense hydrological or operational events, while excluding unrealistically abrupt jumps incompatible with reservoir storage dynamics.

Because no independent inflow or precipitation records are used, individual flagged variations are not attributed to specific causes, and extreme hydrological or operational events cannot be formally excluded. However, the very small fraction of corrected observations limits the influence of this procedure on the derived annual metrics.

Flagged values were treated as missing data and replaced by linear interpolation in time, performed locally and independently for each reservoir. This interpolation was applied only to isolated non-physical points and did not extend across extended time intervals. Across all reservoirs, only 1022 out of 194906 daily observations (0.52%) were flagged by this criterion and locally interpolated. For any single reservoir, the fraction of corrected points remained below 0.92% of the available daily record.

No additional corrections were applied. Values marginally exceeding nominal bounds (e.g. slightly above 100%) were retained, as they can arise from calibration choices, reporting conventions, or operational definitions of reservoir capacity. Seasonal cycles, long-term trends, and interannual variability were preserved in full.

Figure 2 illustrates the effect of this preprocessing step by comparing the raw daily time series with the corresponding annual mean values. The preprocessing does not alter the qualitative behavior of the data and serves solely to remove physically inconsistent artefacts that could bias subsequent aggregation and correlation analyses.

The resulting physically consistent daily records constitute the basis for the computation of annual metrics and all subsequent analyses presented in this work.

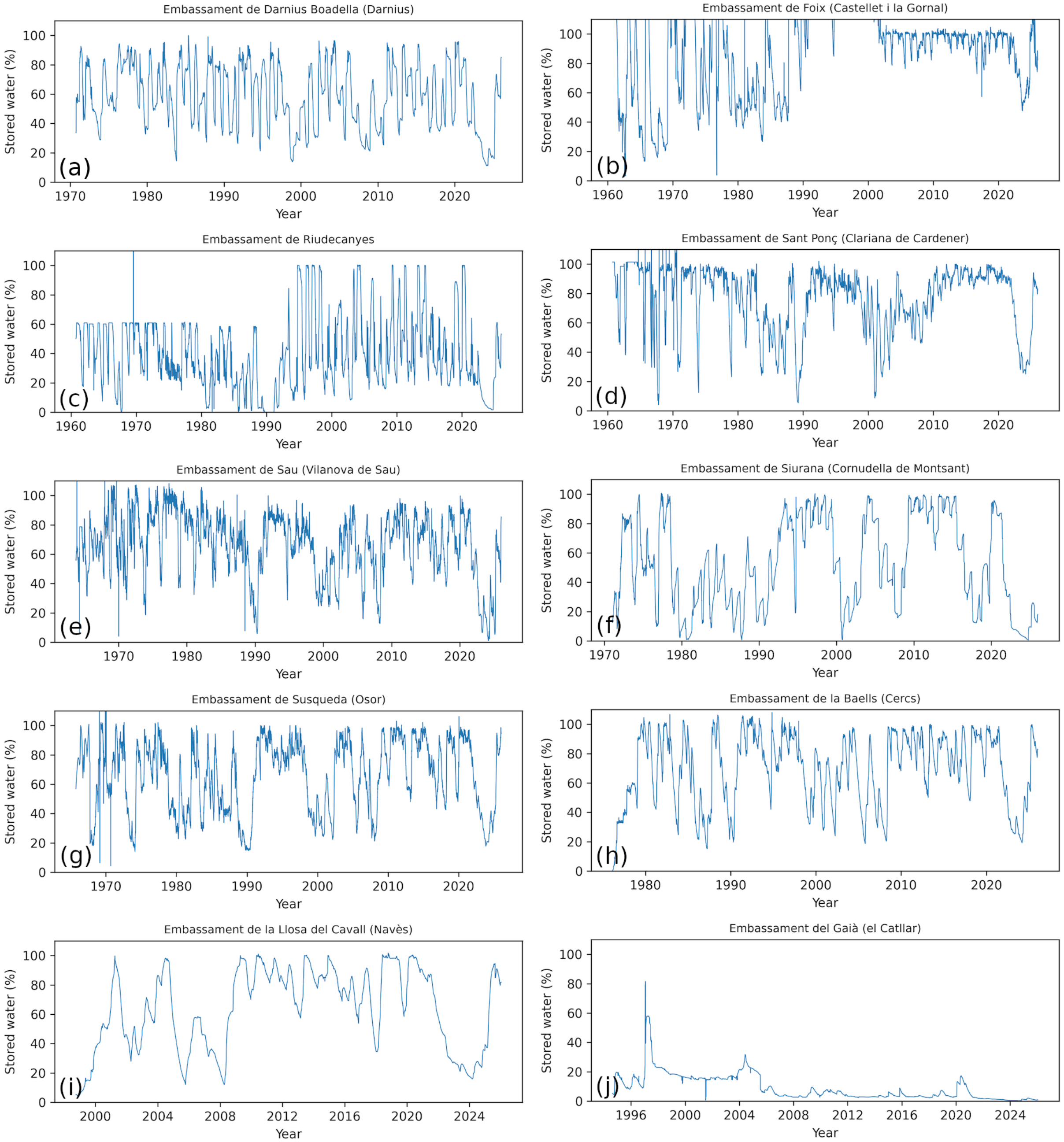

Figure 1. Daily percentage of stored water volume for the analyzed reservoirs, as provided by the Catalan Water Agency (ACA). The data are shown without filtering or smoothing and illustrate the full temporal variability of each reservoir over the observation period.

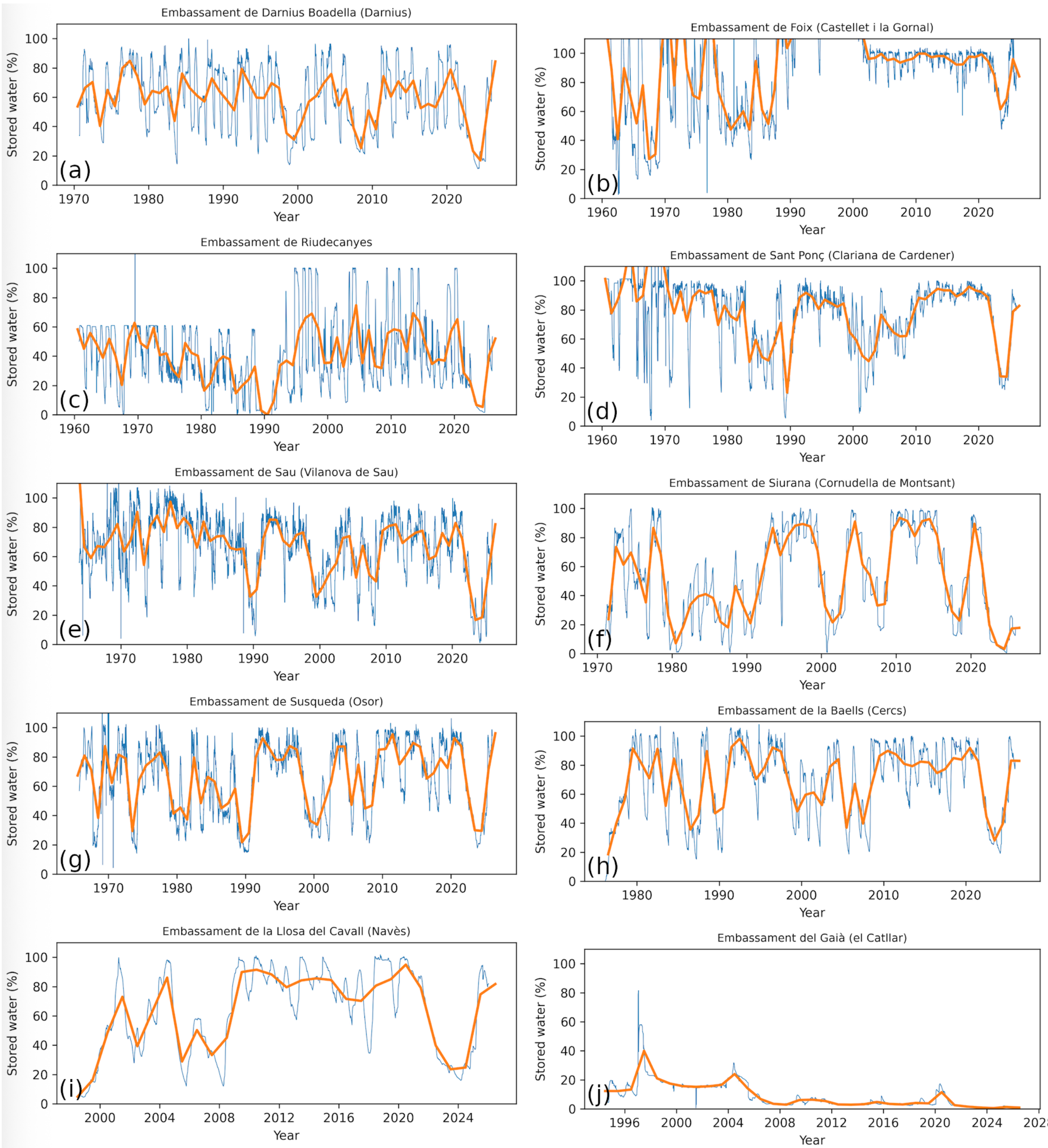

Figure 2. Daily reservoir storage (percentage of stored water volume) for each analyzed reservoir (thin lines), together with the corresponding annual mean values (thick lines). The annual aggregation highlights interannual variability and facilitates comparisons across reservoirs and time periods.

4 Derived Annual Metrics

In order to characterize long-term reservoir storage dynamics while reducing the influence of short-term operational fluctuations, the daily reservoir records were aggregated into a set of annual metrics. Annual aggregation emphasizes interannual and multi-decadal variability, which is the primary focus of the present study.

For each reservoir and each calendar year, the principal metric considered is the *annual mean stored volume percentage*, defined as the arithmetic mean of the daily percentage of stored water volume over that year. This metric provides a compact measure of the overall storage state of the reservoir and reflects persistent wet or dry conditions rather than short-lived events.

In addition to the annual mean, two threshold-based metrics were introduced to characterize low-storage regimes of increasing severity. For each year, the fraction of days during which the stored volume percentage fell below 40% of nominal capacity was computed. This metric captures sustained periods of hydrological stress, during which reservoir operation and water availability may be significantly constrained.

A second, more restrictive threshold was defined at 15% of nominal capacity. The corresponding annual fraction of days below this level was used as an indicator of extreme or crisis-level storage conditions. Such low storage states are often associated with exceptional drought episodes or prolonged deficit periods and occur rarely under normal hydrological variability.

For both threshold-based metrics, annual values were normalized by the number of available daily observations in each year. This normalization ensures comparability across reservoirs and accounts for occasional missing data without biasing the results. Years with insufficient data coverage were excluded from the analysis.

These three annual metrics – annual mean stored volume percentage, fraction of days below 40%, and fraction of days below 15% – provide complementary perspectives on reservoir storage dynamics. The annual mean captures average conditions, while the threshold-based metrics emphasize the timing and persistence of low-storage and extreme drought states. Together, they form a minimal yet informative set of observables for assessing synchronization and collective behavior across reservoirs.

No detrending, standardization, or normalization across reservoirs was applied to the annual metrics prior to analysis. All subsequent results therefore reflect correlations in physically meaningful quantities expressed in their original units and scales.

Calendar-year aggregation was chosen to provide a uniform interannual unit across all reservoirs and to facilitate comparison at multi-decadal scales. This approach is appropriate for the present objective, which focuses on long-term co-variability rather than seasonal dynamics. Possible seasonal effects, including snowmelt contributions in headwater basins, are therefore not resolved explicitly and are instead integrated into the annual metrics.

5 Methods

The objective of the analysis is to quantify the degree of collective behavior among reservoir storage dynamics in Catalonia and to assess whether this behavior changes over time. To this end, correlation-based methods were applied to the annual metrics defined in the previous section.

For each annual metric, pairwise statistical relationships between reservoirs were quantified using the Pearson correlation coefficient. Pearson correlation was chosen because the annual metrics are continuous variables and the primary goal is to measure linear co-variability at interannual time scales. Pearson correlation captures linear dependence and does not fully characterize possible nonlinear or rank-based relationships between reservoirs. The results are therefore interpreted specifically in terms of linear interannual synchronization. For each reservoir pair, correlations were computed using only years for which data were available for both reservoirs. A minimum overlap of ten years was required in order to retain a correlation value, thereby avoiding spurious results driven by short records.

Reservoir pairs were classified according to their river basin affiliation. Pairs belonging to the same basin were labeled as *intra-basin*, while pairs belonging to different basins were labeled as *inter-basin*. This distinction allows correlations arising from shared hydrological inputs or operational coupling within basins to be distinguished from correlations reflecting broader regional coherence across independent basins.

To investigate potential temporal changes in synchronization, the analysis was performed separately for two fixed time intervals: 1960–1986 and 1987–2026. This temporal segmentation was motivated by a visible change in the behavior of several reservoir time series around the mid-1980s, as revealed by exploratory inspection of the annual metrics. The split year was applied uniformly across all reservoirs and metrics and was not optimized to maximize statistical contrast. The resulting conclusions are qualitative in nature and do not rely on the exact choice of a specific transition year. The qualitative increase in inter-basin synchronization is preserved for nearby split years within the mid-1980s window (not shown).

For each time interval and each annual metric, a full correlation matrix was constructed. Correlation coefficients were then grouped into intra-basin and inter-basin subsets. The distributions of these subsets were analyzed using summary statistics, including the mean, median, and interquartile range, in order to characterize systematic differences between basin classes and time periods. Because correlations are retained only when at least ten overlapping years exist for a given reservoir pair, the number of inter-basin pairs can differ across metrics and time intervals depending on data availability.

All analyses were conducted independently for the annual mean stored volume percentage and for each of the two threshold-based metrics. No detrending, normalization, or standardization across reservoirs was applied prior to correlation analysis. This choice ensures that the results reflect correlations in physically meaningful quantities and preserves differences in variability and amplitude between reservoirs.

Common-mode removal and residual correlations

To assess whether the observed increase in inter-basin synchronization can be explained primarily by a dominant empirical mode of co-variability shared across reservoirs, we performed an additional analysis in which the leading common mode of variability was explicitly removed from the annual reservoir metrics.

For each metric, the annual reservoir values were treated as spatial vectors defined over the set of reservoirs available in a given year. Prior to the analysis, the spatial mean was removed independently for each year (over the reservoirs available in that year) in order to isolate co-variability around the contemporaneous regional mean rather than absolute storage levels. A dominant empirical mode of co-variability (PC1) was then estimated from the full set of mean-removed annual vectors using all available years, without imposing the requirement that all reservoirs be present simultaneously in every year. PC1 is interpreted here as an empirical mode of co-variability in the reservoir-storage metrics and not as direct evidence of a uniquely identifiable climatic or operational driver.

Computationally, missing entries in the resulting year-by-reservoir matrix were set to zero in the mean-removed space, and PC1 was obtained as the leading right-singular vector of this matrix. The contribution of this leading mode was subsequently removed year by year by projecting each mean-removed annual vector onto the restriction of PC1 to the reservoirs available in that year and subtracting the corresponding component. This procedure yields residual annual series that represent deviations from the dominant empirical mode of co-variability while preserving basin-specific and higher-order spatial variability.

Pairwise Pearson correlations were then recomputed from these residual series, separately for the 1960–1986 and 1987–2026 periods, using only years common to each reservoir pair and retaining only correlations based on at least ten overlapping years. The resulting residual correlation distributions provide a direct test of whether the enhanced inter-basin synchronization observed in the raw annual metrics persists beyond a single dominant empirical mode of co-variability.

6 Results

6.1 Individual Reservoir Time Series

Figure 1 shows the daily percentage of stored water volume for each analyzed reservoir over the full observation period. The records exhibit pronounced variability on seasonal and interannual time scales, with recurrent episodes of low storage interspersed with wetter periods.

Despite differences in reservoir capacity, basin characteristics, and operational constraints, several broad features are shared across reservoirs. Extended low-storage episodes are visible in multiple systems, particularly during well-known drought periods, although their timing and severity vary among basins. Visual inspection suggests that early decades are characterized by more heterogeneous behavior, whereas later decades display an increased degree of temporal alignment across reservoirs.

The aggregation into annual mean values, shown in Fig. 2, suppresses short-term operational fluctuations and emphasizes interannual and multi-year variability. This representation facilitates direct comparison across reservoirs and highlights coherent long-term behavior emerging in the later part of the record.

6.2 Correlation Structure of Annual Mean Storage

Figure 3 shows the Pearson correlation matrix of annual mean reservoir storage. As expected, reservoirs belonging to the same river basin generally exhibit higher correlations, reflecting shared hydrological inputs and, in some cases, hydraulic or operational coupling.

Positive correlations are also observed between reservoirs located in different basins, indicating the presence of a regional-scale component influencing reservoir storage dynamics beyond basin-specific controls. The broad distribution of inter-basin correlations motivates a more detailed analysis of their temporal structure.

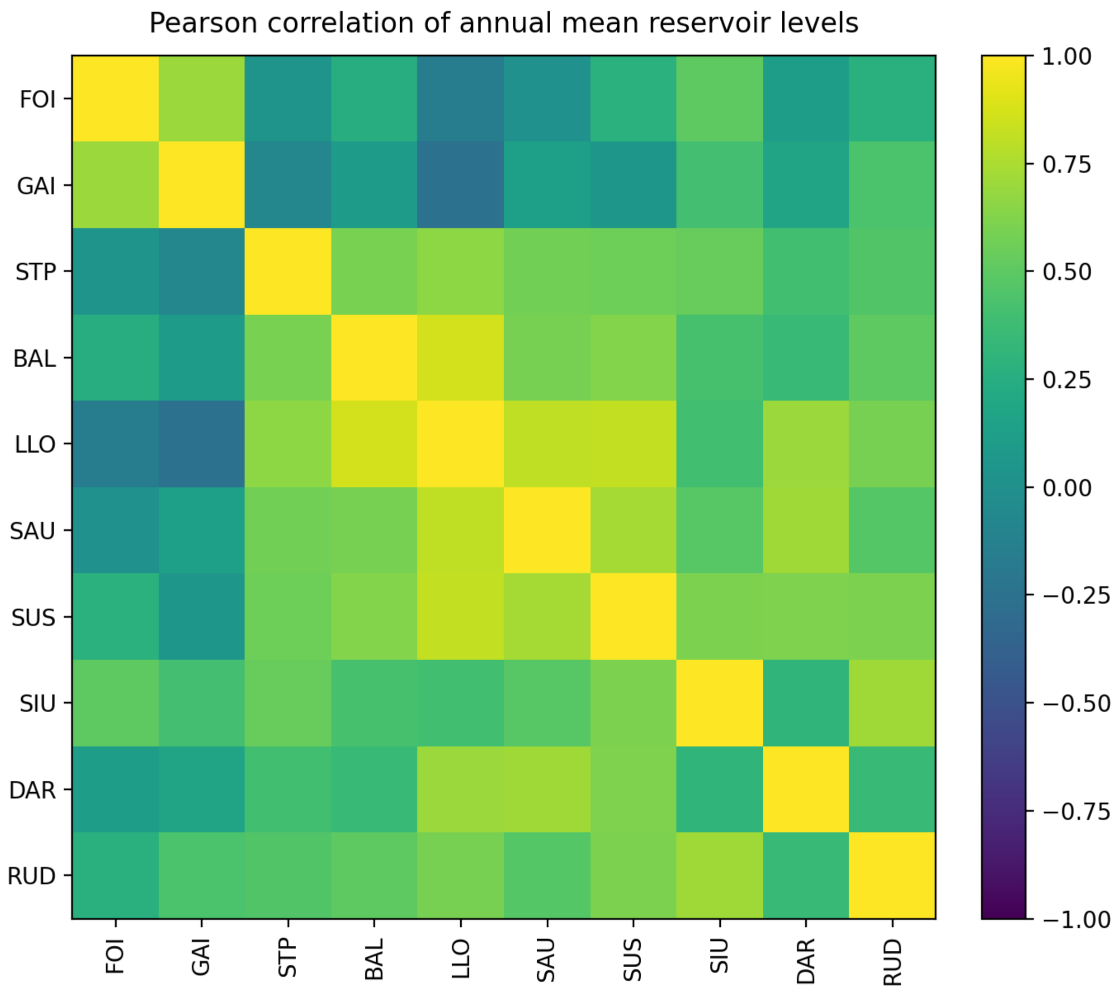

Figure 3. Pearson correlation matrix of annual mean stored volume percentages computed from the ACA daily records after physically consistent preprocessing and annual aggregation. Reservoirs are ordered by river basin affiliation to highlight intra-basin coherence and inter-basin synchronization. Correlations are computed using only overlapping years for each reservoir pair, requiring at least ten common years. Reservoir abbreviations and basin affiliation (in the order shown): FOI (Foix), GAI (Gaià), STP (Llobregat), BAL (Llobregat), LLO (Llobregat), SAU (Ter), SUS (Ter), SIU (Ebre), DAR (Muga), RUD (Riudecanyes).

6.3 Temporal Segmentation and Inter-Basin Synchronization

Figure 4 compares the distribution of inter-basin correlation coefficients before and after 1986. In the earlier period, correlations are broadly distributed around low values, indicating limited synchronization across independent basins. In contrast, the post-1986 distribution is shifted toward higher values, with increased mean and median correlations and reduced weight at near-

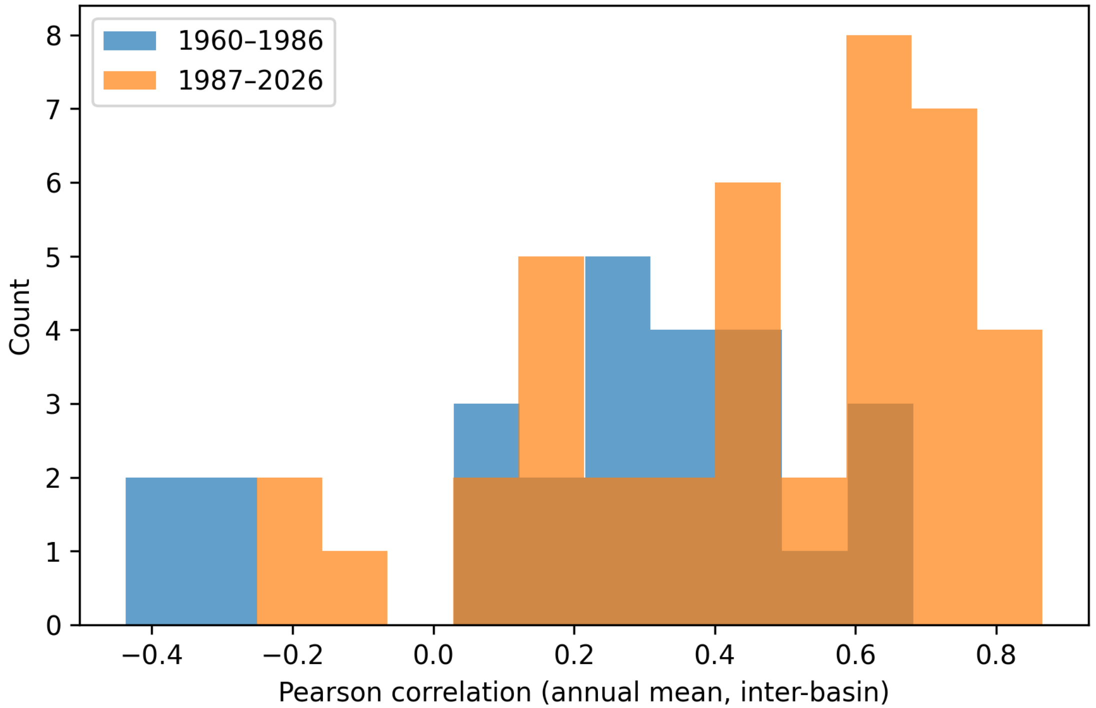

Figure 4. Distribution of Pearson correlation coefficients for *inter-basin* reservoir pairs, computed from annual mean stored volume percentages. The comparison between 1960–1986 and 1987–2026 shows a systematic shift toward higher correlations in the later period, indicating increased regional synchronization across independent basins.

zero values. This shift indicates enhanced synchronization of interannual reservoir storage variability across basins in the later decades.

6.4 Moderate Low-Storage Conditions

For the fraction of days per year with stored volume below 40% of nominal capacity, Fig. 5 reveals a pronounced contrast between the two periods. Prior to 1986, correlations are weak and widely scattered, consistent with basin-specific moderate drought behavior. In the later period, the distribution shifts toward higher positive correlations, indicating that sustained low-storage conditions increasingly occur in a coordinated manner across basins.

6.5 Extreme Low-Storage Events

The strongest temporal contrast is observed for extreme low-storage conditions, characterized by the fraction of days per year below 15% of nominal capacity (Fig. 6). In the early period, correlations cluster around zero, indicating largely asynchronous

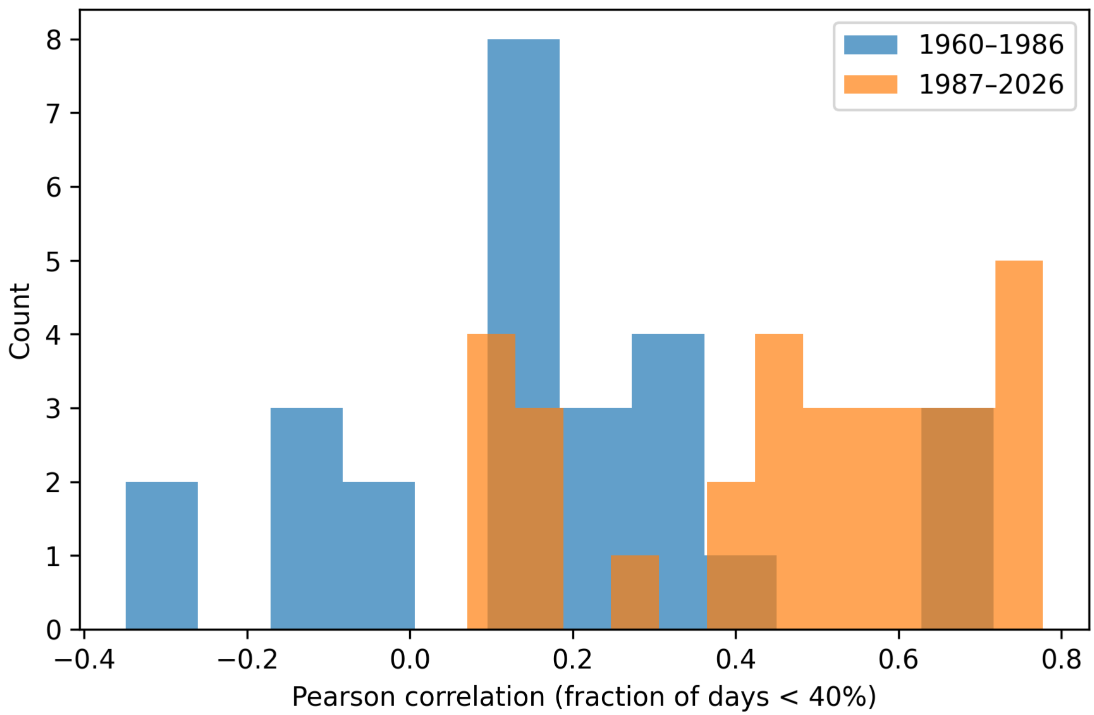

Figure 5. Distribution of Pearson correlation coefficients for *inter-basin* reservoir pairs, computed from the annual fraction of days with stored volume below 40% of nominal capacity. Inter-basin synchronization is substantially stronger in 1987–2026 than in 1960–1986.

extreme events across basins. After 1986, correlations become systematically positive, suggesting that severe low-storage conditions increasingly occur simultaneously across independent systems.

6.6 Common-mode removal (PC1) and residual inter-basin structure

To test whether the observed increase in inter-basin correlations reflects emergent inter-basin coupling or the dominance of a shared empirical mode of co-variability, the correlation analysis was repeated after removal of the leading principal component (PC1) of the annual reservoir metrics.

After removal of PC1, inter-basin correlations are strongly reduced for all three metrics. The distributions of residual correlations are centered closer to zero and exhibit substantially less contrast between the pre- and post-1986 periods. Quantitatively, the inter-basin mean correlation increases from 0.273 to 0.464 for the annual mean metric in the raw data, whereas it changes only from -0.172 to -0.097 after PC1 removal. Analogous reductions in pre/post contrast are observed for the low-storage metrics: from 0.169 to 0.471 (fraction below 40%) versus -0.139 to -0.098 after PC1 removal, and from 0.041 to 0.206 (fraction below 15%) versus 0.176 to -0.010 after PC1 removal. While some dispersion remains, particularly for extreme low-

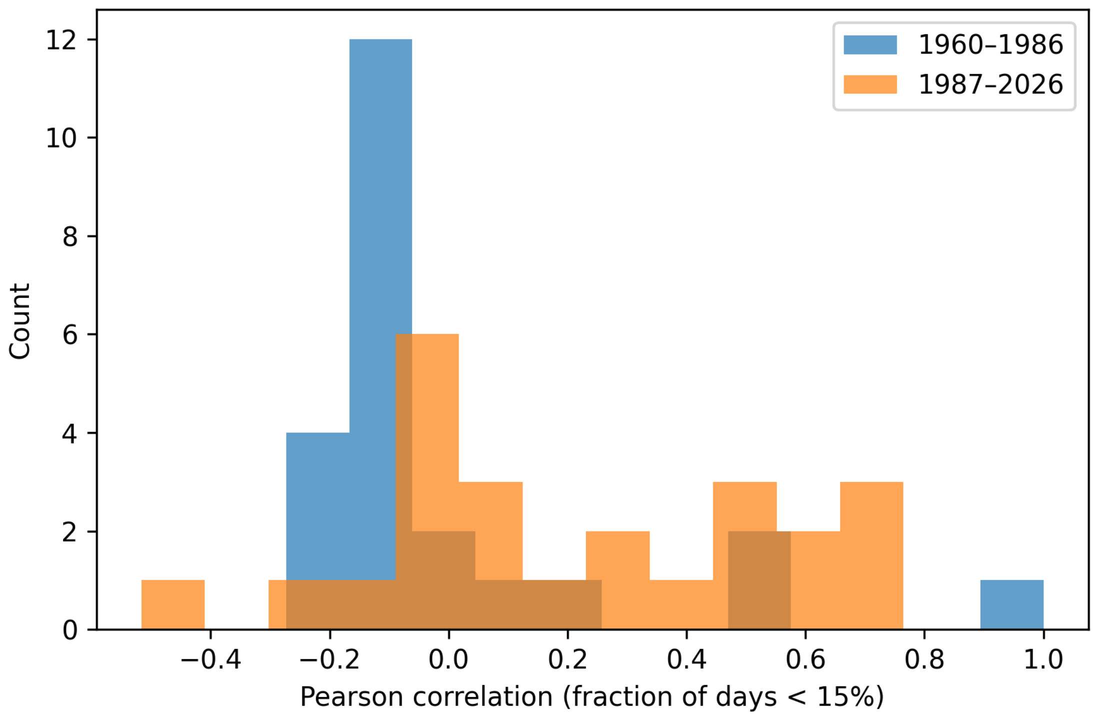

Figure 6. Distribution of Pearson correlation coefficients for *inter-basin* reservoir pairs, computed from the annual fraction of days with stored volume below 15% of nominal capacity. Extreme low-storage events become increasingly synchronized across basins after 1986.

storage metrics, the systematic shift toward higher correlations observed in the raw data largely disappears once the dominant common mode is removed.

6.7 Summary of Observational Findings

Taken together, the results indicate an apparent transition from predominantly basin-confined variability in the early decades to enhanced inter-basin synchronization in the later period. This transition affects annual mean storage conditions and is even more pronounced for low-storage and extreme drought metrics.

However, the PC1-removal analysis demonstrates that a large fraction of this increased synchronization is captured by a single dominant empirical mode of co-variability. Once this common component is removed, the residual inter-basin correlations are substantially weaker within the present pairwise correlation framework and show a much reduced pre/post contrast. At the level of the annual metrics analyzed here, additional inter-basin structure beyond this dominant mode appears weaker within the annual pairwise correlation framework used here.

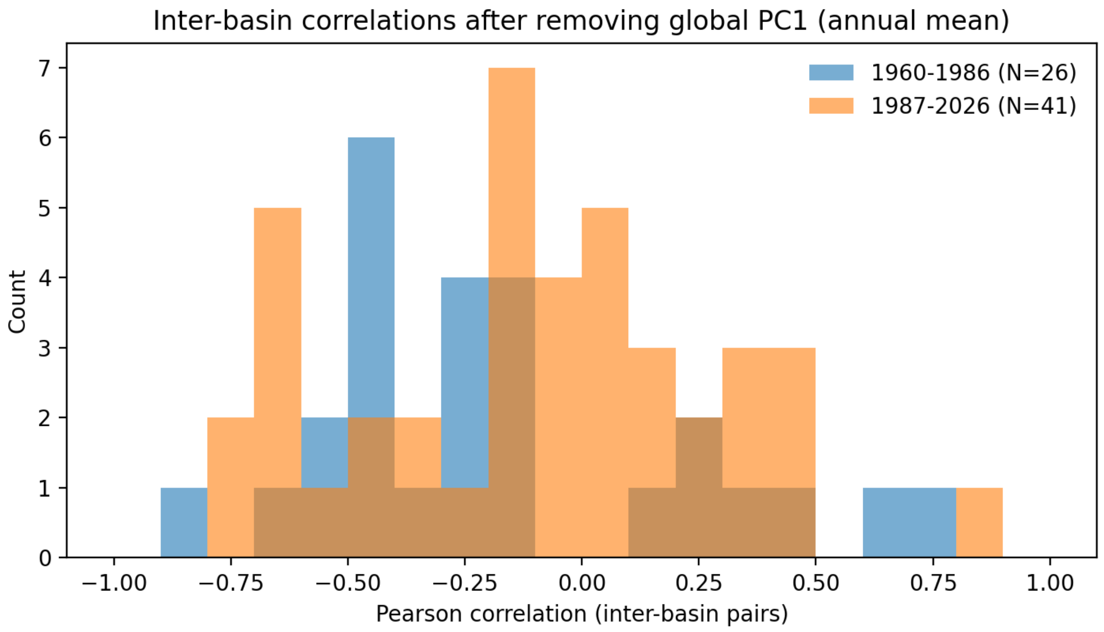

Figure 7. Distribution of Pearson correlation coefficients for *inter-basin* reservoir pairs computed from the residual annual mean stored volume percentages after removal of the leading common mode (PC1).

7 Discussion

This study is based exclusively on long-term observational reservoir records and addresses a focused question: how coherent are reservoir storage dynamics across basins, and whether that coherence has changed over time. The pre/post comparison reveals a marked increase in inter-basin correlations for annual mean storage conditions and, even more strongly, for low-storage and extreme drought metrics after the mid-1980s.

A key clarification is provided by the common-mode (PC1) removal analysis. When the leading regional component shared by all reservoirs is subtracted year by year, inter-basin correlations are substantially reduced and the contrast between the early and late periods is strongly weakened. This indicates that the dominant contribution to the apparent synchronization is more consistent with the strengthening of a dominant empirical mode of co-variability than with the emergence of complex multi-factor inter-basin coupling.

This distinction is important for interpretation. A basin-spanning change in hydroclimatic forcing or in large-scale boundary conditions can imprint a common mode on all reservoirs, producing increased inter-basin correlations even if basin-specific deviations remain largely independent. In this picture, the reservoir network behaves, to first order, as a collection of systems driven by one dominant empirical component plus smaller local contributions.

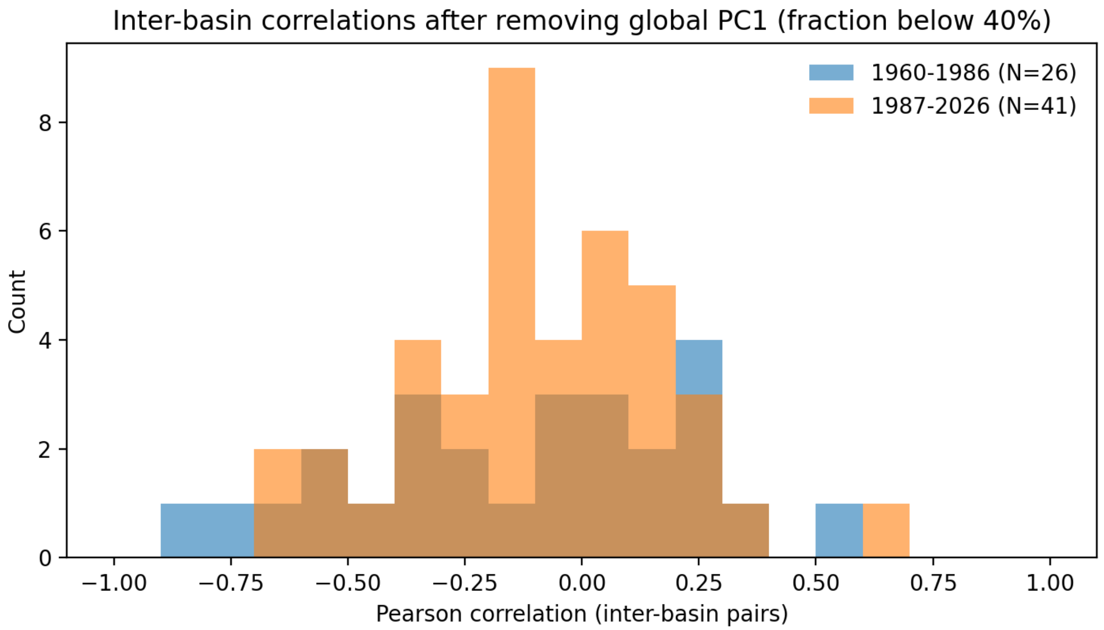

Figure 8. Same as Fig. 7, but for the residual annual fraction of days with stored volume below 40% of nominal capacity.

From a water-management perspective, this result remains highly relevant. Reservoir storage is not a purely natural hydrological variable. It integrates hydroclimatic inputs with operational decisions, allocation rules, and infrastructure constraints. The synchronization identified here therefore reflects the behavior of the managed reservoir system, rather than natural hydrological coherence alone. In this context, coordinated responses may arise from both shared external forcing and management practices acting across multiple basins. Even if synchronization arises primarily from a common mode rather than direct coupling, its practical effect is the same: drought-relevant conditions increasingly occur simultaneously across basins, reducing the effectiveness of spatial diversification and inter-basin compensation strategies.

This interpretation can be placed in the broader context of Mediterranean hydroclimatic variability, where large-scale drought patterns, atmospheric circulation anomalies, and changes in evaporative demand have been widely documented (Lionello, 2012; Vicente-Serrano et al., 2014). While the present analysis does not explicitly incorporate external climatic datasets, such processes provide a plausible background for the emergence of coherent inter-basin behavior and large-scale empirical co-variability at regional scale.

The present work intentionally refrains from causal attribution. Similarly, the correlation analysis is intended as a characterization of large-scale linear co-variability and does not exclude the presence of additional nonlinear dependence structures not resolved by the present approach. Determining whether the strengthened empirical mode of co-variability originates from changes in atmospheric circulation, precipitation regimes, evaporative demand, land use, or reservoir operating rules requires external datasets and dedicated attribution analyses. The contribution of this study is instead to establish a clean observational

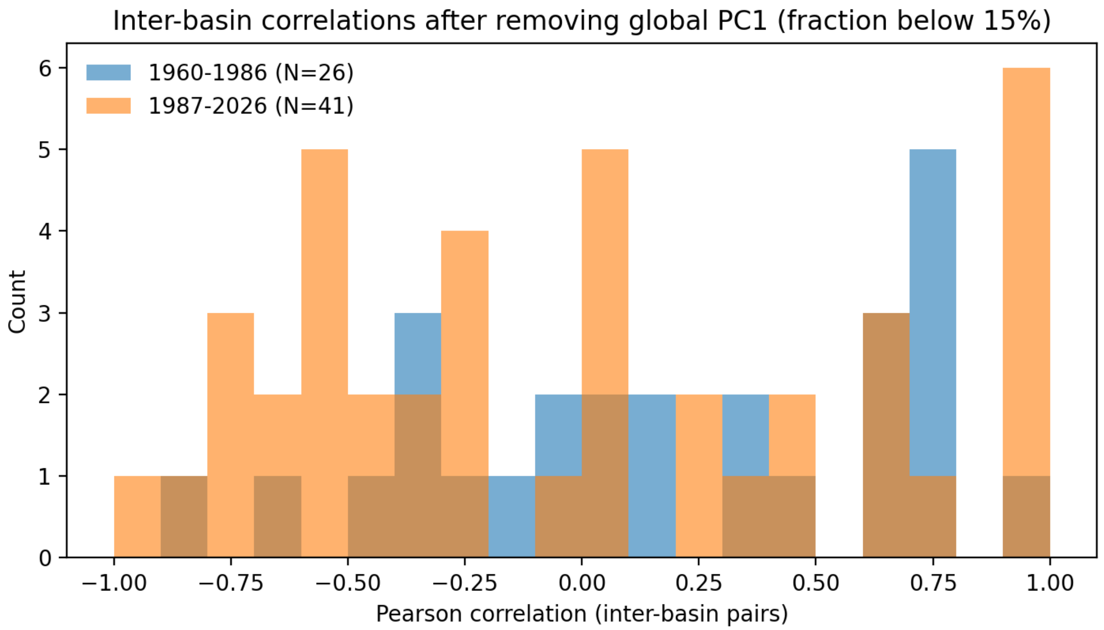

Figure 9. Same as Fig. 7, but for the residual annual fraction of days with stored volume below 15% of nominal capacity.

baseline and to demonstrate, in a statistically controlled manner, that the increased inter-basin coherence is largely captured by a single dominant empirical mode of co-variability.

8 Conclusions

This study presents a long-term observational analysis of reservoir storage dynamics in Catalonia, based exclusively on daily records of stored water volume percentages spanning the period 1960–2026. By combining physically consistent preprocessing with the definition of robust annual metrics, the analysis provides a unified framework for comparing reservoir behavior across multiple basins and over multi-decadal time scales using a consistent observational approach directly grounded in system-level data.

The results reveal a clear change in the collective dynamics of the system. While earlier decades are characterized by predominantly basin-specific variability, the period after the mid-1980s exhibits a marked increase in inter-basin synchronization. This transition is visible in annual mean storage conditions and is even more pronounced for metrics associated with sustained low-storage conditions and extreme drought states, which are the conditions of greatest practical relevance for water-resource management (Van Loon, 2015).

Crucially, the increased synchronization is shown to be largely explained by a single dominant empirical mode of co-variability. After removal of this leading common component, residual inter-basin correlations are strongly reduced and the pre/post contrast is substantially weakened. At the level of the annual metrics analyzed here, additional inter-basin structure beyond this dominant mode appears weaker within the annual pairwise correlation framework used here, indicating that the apparent increase in coordination across basins primarily reflects the growing influence of a shared dominant empirical mode of co-variability rather than enhanced direct coupling between systems.

Rather than identifying causal drivers, this work establishes a rigorous observational baseline for future studies. By clearly characterizing the nature, timing, and structure of regional coherence in reservoir storage dynamics, the analysis constrains subsequent attribution efforts and provides a reference framework for investigations incorporating climatic, atmospheric, or operational variables, which are necessary to interpret the origin of the identified empirical mode of co-variability.

Overall, the results highlight the value of long-term, multi-reservoir analyses for detecting emergent regional behavior in managed hydrological systems and emphasize the relevance of coordinated regional planning in the presence of spatially coherent drought risk, where simultaneous stress across basins limits the effectiveness of local mitigation strategies and requires system-level responses (Stahl et al., 2010). Although the analysis focuses on Catalonia, the approach and findings are applicable to other multi-reservoir systems subject to shared hydroclimatic forcing.

Author contributions. Carles Serrat designed the study, performed the analysis, and wrote the manuscript.

Competing interests. The author declares that there are no competing interests.

Data availability. The reservoir storage data used in this study are provided by the Catalan Water Agency (Agència Catalana de l'Aigua, ACA) and are available from the agency upon request.

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