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Hydrological Memory Regulates River Basin Recovery from Climate Extremes: Evidence from China's Major River Basins

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Abstract Hydrological memory from climate extremes depends not only on disturbance magnitude but also on the persistence of antecedent basin storage. This study developed a Hydrological Memory Framework (HMF) to quantify basin-scale hydrological memory and assess its influence on resilience across eight major river basins in China during 1981–2025. Hydrological memory was estimated using the Catchment Forgetting Curve (CFC), while drought and flood recovery were evaluated from standardized hydrological anomalies. Principal Component Analysis, Random Forest regression, generalized additive models, and mixed-effects modelling were used to identify environmental controls and quantify the memory–resilience relationship. Hydrological memory varied markedly among basins, from less than 3 years in the humid Yangtze and Pearl basins to approximately 5–6 years in the arid Heihe and Tarim basins. Recovery time increased strongly with memory duration ($R^2 = 0.81$, $p < 0.001$), and drought recovery was generally two to three times longer than flood recovery. Mixed-effects modelling confirmed hydrological memory as the dominant predictor of recovery time ($\beta = 0.68$, $p < 0.001$), with the full model explaining 84% of the observed variability. Random Forest analysis identified groundwater storage (28.4%), climatic aridity (22.7%), soil moisture persistence (17.9%), and basin elevation (12.6%) as the principal controls on memory. The results show that antecedent storage exerts a measurable control on post-extreme recovery and basin resilience. The HMF provides a process-based basis for identifying vulnerable basins and improving climate-adaptive water resources management.

Keywords: Hydrological memory, River basin resilience, Climate extremes, Catchment Forgetting Curve, Random Forest

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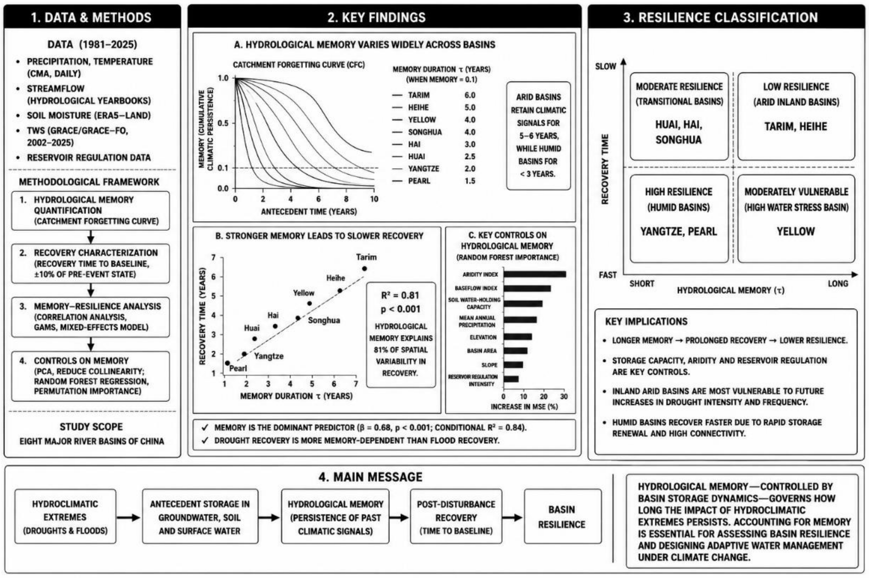
Graphical Abstract



1. Introduction

Climate change is reshaping the global water cycle, with droughts and floods becoming more frequent, persistent, and severe in many regions. Changes in temperature and precipitation, together with higher evaporative demand, are altering water availability and hydrological responses across river basins. These shifts increasingly challenge reliable water supply, ecosystem functioning, and the long-term management of freshwater resources (IPCC, 2023, Blöschl et al., 2019). Over recent decades, recurrent droughts and floods have pushed many river basins beyond their historical range of hydrological variability. Such disturbances increase hazard exposure while also weakening the capacity of freshwater systems to sustain ecological processes and meet human water demands under a changing climate (Granata and Di Nunno, 2026, Grill et al., 2019, Gudmundsson et al., 2021a).

River basins respond to climatic forcing with a time lag because precipitation is redistributed and retained across interconnected stores, including soil moisture, groundwater, wetlands, snowpack, reservoirs, and river channels (Nile et al., 2025). These storage components shape runoff timing and magnitude by retaining water and releasing it over different timescales, creating a delayed basin response to climatic variability (Sun et al., 2023, McDonnell and Beven, 2014, Fan et al., 2023). Storage therefore gives river basins a hydrological legacy: present conditions reflect not only current weather but also water retained from earlier weeks, months, or years. This persistence of past climatic influence, termed hydrological memory, governs how quickly a basin adjusts after external disturbances (Nippgen et al., 2016, Kumar et al., 2025, Orth et al., 2022).

Hydrological memory is especially relevant under climate change because basin storage shapes both the propagation of extremes and the pace of recovery. Groundwater and soil-water reserves can buffer short-term anomalies, but their slow recharge and release may prolong recovery after severe droughts or floods (Riedel and Weber, 2020, Maxwell and Condon, 2016). By contrast, basins with limited storage tend to respond quickly but are less able to buffer climatic disturbances. This contrast shows that resilience depends not only on climate forcing, but also on how effectively a basin stores, transfers, and releases water over time. Understanding these storage controls is therefore central to explaining differences in hydrological recovery among river basins (Wada, 2024, Bierkens and Wada, 2019).

Although drought propagation, flood generation, runoff dynamics, groundwater behavior, soil moisture persistence, and hydrological connectivity have been widely studied, these processes are often examined separately or through individual hydrological variables (Gupta et al., 2023, Galelli et al., 2025). Considerable advances have been achieved in identifying meteorological and hydrological extremes using indices such as the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Standardized Streamflow Index (SSI) (Baez-Villanueva et al., 2024, Shamshirband et al., 2020). Earth observation, land-surface models, and distributed hydrological models have improved estimates of basin water storage and hydrological variability. However, these tools are still used mainly to characterize the magnitude and spatial pattern of extremes, offering less insight into why basins exposed to similar disturbances can recover at very different rates (Vicente-Serrano et al., 2022, Gudmundsson et al., 2021b).

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A persistent limitation in hydrological research is the tendency to characterize memory through separate indicators such as soil moisture persistence, groundwater recession, streamflow autocorrelation, or terrestrial water storage anomalies. Although these metrics are useful for identifying storage behavior within individual components of the hydrological system, they do not fully represent the collective response of a river basin, where multiple storage pathways interact over different temporal scales. Consequently, hydrological memory is still not well resolved as an integrated basin-scale property, and its influence on recovery after droughts and floods remains incompletely understood. This gap constrains the development of process-based resilience assessments and makes it difficult to explain why basins experiencing similar climatic disturbances often show markedly different recovery trajectories (Knoben et al., 2024, McMillan et al., 2025)

Hydrological resilience reflects the capacity of a river basin to absorb climatic disturbances, sustain essential hydrological functions, and recover toward its pre-disturbance state. The pace of recovery is controlled not only by the magnitude of the climatic shock but also by antecedent storage conditions within groundwater, soil, wetlands, lakes, glaciers, and reservoirs. These storage components can moderate short-term extremes by buffering water deficits or excesses, yet their slow recharge and release may also prolong recovery once the disturbance has passed. In contrast, basins with limited storage often respond more rapidly to changing climate conditions but are generally less capable of withstanding persistent droughts or floods. River basin resilience therefore emerges from the interaction between external climatic forcing and the duration, capacity, and turnover of internal water storage (Bruno et al., 2026, Berghuijs et al., 2025). Recent advances in satellite gravimetry, reanalysis products, and machine-learning methods have substantially improved the ability to track terrestrial water storage and characterize basin-scale hydrological behavior. GRACE and GRACE-FO, in particular, provide direct information on large-scale storage variability that cannot be captured from streamflow observations alone. Yet these tools are still commonly applied in isolation rather than within a unified analytical framework. As a result, the combined influence of antecedent storage, climatic persistence, and recovery dynamics on basin resilience remains insufficiently resolved. Integrating these data sources and analytical approaches offers a stronger basis for quantifying hydrological memory as a basin-scale property and for explaining differences in post-extreme recovery across contrasting river systems (Karki et al., 2025, Springer et al., 2026).

To address these limitations, this study introduces a Hydrological Memory Framework (HMF) that defines hydrological memory as a basin-scale property emerging from the interaction of climatic forcing, internal water storage, and runoff response. Rather than treating soil moisture, groundwater, and streamflow as separate indicators, the framework combines long-term climatic persistence with post-event recovery to describe how climatic signals are stored, transferred, and progressively released within a river basin. A central component of the HMF is the Catchment Forgetting Curve (CFC), which tracks the decline in the influence of antecedent climatic conditions on present runoff. In contrast to conventional autocorrelation-based measures, the CFC estimates how long past climate continues to shape runoff generation, providing a physically interpretable measure of effective hydrological memory that can be compared across basins with different climatic and physiographic characteristics (De Lavenne et al., 2022).

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China provides a strong setting for evaluating this framework because its major river basins span an unusually broad hydroclimatic gradient, from humid subtropical monsoon regions to hyper-arid inland systems, while also including alpine, snow-influenced, temperate, and heavily regulated catchments. This diversity creates pronounced contrasts in precipitation regime, groundwater dependence, snow storage, vegetation cover, and water management, allowing the controls on hydrological memory to be examined across markedly different basin types. In addition, more than four decades of hydrometeorological observations provide sufficient temporal coverage to assess long-term climatic persistence and compare basin recovery across repeated drought and flood events (Hao et al., 2021). Accordingly, this study has four objectives: (i) to quantify hydrological memory across eight major river basins in China using the Catchment Forgetting Curve (CFC); (ii) to determine how memory influences basin resilience and recovery after droughts and floods; (iii) to identify the main climatic and physiographic controls on hydrological memory using statistical and machine-learning methods; and (iv) to develop a transferable Hydrological Memory Framework (HMF) that links climatic persistence, basin storage, and recovery dynamics. By connecting hydrological memory directly with post-event recovery, the study provides a process-based basis for interpreting differences in basin resilience and for improving the assessment of river-basin responses to increasing climate variability.

2. Methodology

Hydrological recovery after climate extremes is shaped by more than the severity of the disturbance itself; it also reflects how strongly antecedent conditions persist within the basin. Conventional assessments often examine precipitation, streamflow, groundwater storage, or drought characteristics separately, which makes it difficult to explain why basins exposed to similar events can recover at very different rates. Here, hydrological memory is treated as a measurable basin-scale property representing the persistence of antecedent hydrological conditions and their influence on resilience. The methodological framework therefore derives hydrological memory from long-term hydroclimatic records and evaluates how differences in memory are related to post-event recovery across eight major river basins in China.

2.1. Study area

China encompasses a broad hydroclimatic gradient, extending from humid subtropical monsoon regions in the southeast to hyper-arid inland environments in the northwest. Eight major river basins—the Yangtze, Yellow, Pearl, Huai, Hai, Songhua, Tarim, and Heihe (Figure 1)—were selected to represent the principal climatic, hydrological, and physiographic contrasts across the country (Liu et al., 2017). Together, these basins represent humid, temperate, semi-arid, arid, alpine, and cold continental environments, with marked contrasts in precipitation, temperature, terrain, groundwater storage, vegetation cover, and human regulation (Wang et al., 2022, Su et al., 2022). Hydrological processes also differ markedly among the selected basins, ranging from precipitation-dominated runoff in humid regions to groundwater- and glacier-fed systems in arid inland catchments. This diversity in climatic forcing and storage conditions provides a strong natural basis for examining spatial differences in hydrological memory and assessing how those differences influence river basin resilience to climate extremes (Chen et al., 2015, Fan et al., 2026).

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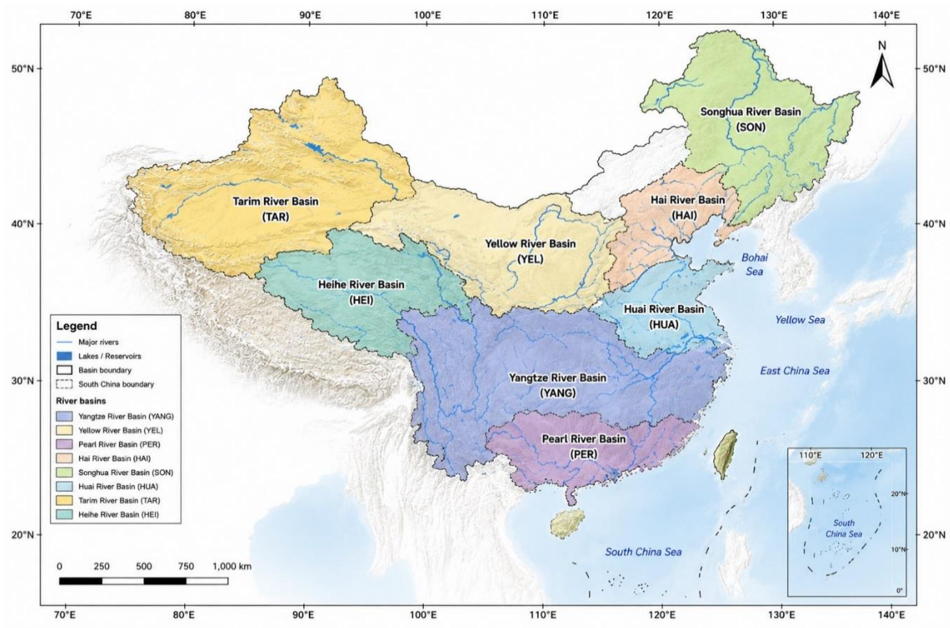

Figure 1. Location of the eight representative river basins investigated in this study. Basin boundaries are superimposed on a shaded-relief basemap of China. Basemap source: Natural Earth; elevation data derived from the Shuttle Radar Topography Mission (SRTM).

The analysis covered the period from 1981 to 2025, encompassing more than four decades of climatic variability, recurrent droughts and floods, accelerated warming, and marked changes in monsoon behavior. This extended record captures a broad range of hydroclimatic conditions, providing sufficient temporal variability to quantify long-term basin memory and assess recovery following both drought and flood events across the eight river basins summarized in Table 1.

Table 1: Hydroclimatic and physiographic characteristics of the eight major river basins investigated in this study.

River Basin	Climate Zone	Basin Area (10^3 km²)	Mean Annual Precipitation (mm)	Mean Annual Temperature (°C)	Mean Elevation (m)	Aridity Index (PET/P)	Dominant Hydrological Storage
Yangtze	Humid subtropical monsoon	1,808	1,100	14.8	1,900	0.85	Surface water + Groundwater
Yellow	Semi-arid temperate monsoon	752	470	9.2	2,450	2.10	Groundwater + Reservoir storage
Pearl	Humid	453	1,480	20.7	780	0.72	Surface water

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River Basin	Climate Zone	Basin Area (10^3 km^2)	Mean Annual Precipitation (mm)	Mean Annual Temperature (°C)	Mean Elevation (m)	Aridity Index (PET/P)	Dominant Hydrological Storage
	subtropical monsoon						
Huai	Humid–semi-humid transitional	270	910	14.5	220	1.18	Soil moisture
Hai	Semi-humid temperate monsoon	318	535	11.9	620	1.86	Groundwater
Songhua	Cold humid continental	557	575	3.9	640	1.42	Snowpack + Soil moisture
Tarim	Hyper-arid inland	1,020	82	10.6	1,210	18.30	Groundwater
Heihe	Arid continental	143	128	7.3	2,060	9.80	Groundwater + Glacier melt

2.2. Datasets

Hydrological memory is governed by the interaction between climatic forcing and basin water storage. Accordingly, only variables directly representing these processes were included in the analysis. Daily precipitation and air temperature were used to characterize climatic forcing, whereas observed streamflow represented the integrated basin-scale hydrological response. Root-zone soil moisture was selected to quantify storage persistence, while terrestrial water storage anomalies (TWSA) derived from the GRACE and GRACE-FO missions (2002–2025) were incorporated to independently validate long-term storage dynamics. Meteorological observations were obtained from the China Meteorological Administration, streamflow data acquired from the Ministry of Water Resources, root-zone soil moisture from ERA5-Land, and TWSA from the GRACE/GRACE-FO missions (Table 2). Before analysis, all datasets underwent quality control, were aggregated to a common monthly resolution, and were spatially averaged within watershed boundaries to ensure a consistent representation of long-term basin-scale hydrological conditions (Muñoz-Sabater et al., 2021, Landerer and Swenson, 2012, Wang et al., 2026).

To facilitate direct comparison among variables measured in different physical units, standardized anomalies were calculated in Eq. （1）:

$$Z_t = \frac{X_t - \mu}{\sigma} \tag{1}$$

where X_t denotes the monthly observation at time t, μ is the long-term monthly mean, and σ is the corresponding standard deviation. Standardization removes seasonal differences while preserving interannual variability and

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long-term climatic signals, allowing persistence characteristics to be compared consistently among climatic forcing, hydrological response, and storage variables.

Table 2： Hydroclimatic variables and data sources used for hydrological memory and resilience assessment.

Variable	Dataset / Source	Spatial Resolution	Temporal Resolution	Study Period	Purpose
Precipitation	China Meteorological Administration (CMA)	Station / Basin	Daily	1981–2025	Climate forcing
Air Temperature	China Meteorological Administration (CMA)	Station / Basin	Daily	1981–2025	PET calculation
Streamflow	Ministry of Water Resources of China	Gauging station	Daily	1981–2025	Basin response
Soil Moisture	ERA5-Land	0.1°	Monthly	1981–2025	Storage persistence
Terrestrial Water Storage	GRACE / GRACE-FO	0.5°	Monthly	2002–2025	Storage validation
Basin Boundary	HydroBASINS / Ministry of Water Resources	Vector	Static	—	Spatial analysis

Hydrological extremes were identified prior to memory analysis because hydrological memory can only be quantified in response to disturbances that alter basin storage. Meteorological droughts were characterized using the Standardized Precipitation Evapotranspiration Index (SPEI), whereas hydrological droughts were identified using the Standardized Streamflow Index (SSI). Flood events were extracted from observed streamflow using basin-specific seasonal high-flow thresholds derived from historical discharge records. For each event, the onset, duration, peak magnitude, cumulative severity, and recovery period were determined, providing a consistent basis for subsequent hydrological memory analysis (Wang et al., 2020, Shamshirband et al., 2020, Lema et al., 2024, Lu et al., 2025).

2.3. Hydrological Memory and Extreme-Event Recovery

River basins respond to climatic forcing through delayed storage and release processes, as precipitation is partitioned among runoff, soil moisture, groundwater, and channel storage. Consequently, present hydrological conditions reflect both contemporary and antecedent climatic forcing. This persistence, termed hydrological memory, represents the capacity of a basin to retain climatic information and influence subsequent hydrological responses. Because storage characteristics differ with climate, geology, topography, vegetation, and human activities, hydrological memory varies among basins, resulting in distinct recovery trajectories following comparable climate extremes (Tonkin et al., 2026, Granata and Di Nunno, 2026).

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In this study, hydrological memory is defined as an integrated basin-scale property that emerges from the interaction among climatic forcing, basin storage, and runoff response, rather than from the persistence of any single hydrological variable. The proposed Hydrological Memory Framework (HMF) links long-term climatic persistence with post-event recovery to quantify basin memory and assess its role in river basin resilience. Hydrological memory was estimated using the Catchment Forgetting Curve (CFC), which represents the gradual decline in the influence of antecedent climatic conditions on runoff generation. In contrast to conventional autocorrelation-based measures, the CFC provides a direct estimate of how long previous climatic conditions continue to shape the present hydrological response. Annual runoff yield for each river basin was calculated in Eq. (2) as follows (Ziang et al., 2025):

$$q_{b,t} = \frac{Q_{b,t}}{A_b} \tag{2}$$

where $Q_{b,t}$ is the annual streamflow volume of basin b during year t, and A_b is the corresponding drainage area. Climatic forcing was represented by the basin humidity index in Eq. (3)

$$H_{b,t} = \frac{P_{b,t}}{PET_{b,t}} \tag{3}$$

where $P_{b,t}$ and $PET_{b,t}$ denote annual precipitation and potential evapotranspiration, respectively. Because climatic conditions differ substantially among China's major river basins, both runoff yield and humidity index were transformed into normalized anomalies to facilitate inter-basin comparison in Eq. (4) and Eq. (5),

$$q'_{b,t} = \frac{q_{b,t} - \bar{q}_b}{\bar{q}_b} \tag{4}$$

$$H'_{b,t} = \frac{H_{b,t} - \bar{H}_b}{\bar{H}_b} \tag{5}$$

where $\bar{q}_b$ and $\bar{H}_b$ represent the long-term basin means. These normalized anomalies describe the relative departure of hydrological conditions from the long-term climatological state while eliminating differences associated with basin size and climatic magnitude.

The contribution of antecedent climatic conditions to present runoff was subsequently estimated using a distributed lag regression in Eq. (6),

$$q'_{b,t} = \alpha_b + \sum_{j=0}^{J} \beta_{b,j} H'_{b,t-j} + \varepsilon_{b,t}, \tag{6}$$

where α_b is the basin-specific intercept, $\beta_{b,j}$ represents the contribution of climatic conditions occurring j years before the present year, and $\varepsilon_{b,t}$ denotes the residual error. The regression coefficients therefore describe how rapidly climatic information is forgotten by each river basin. Larger coefficients associated with longer antecedent periods indicate that previous climatic conditions continue to exert a measurable influence on present hydrological behaviour, reflecting stronger basin memory.

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To facilitate comparison among river basins, the regression coefficients were normalized to construct the Catchment Forgetting Curve in Eq.（7）,

$$F_b(j) = \frac{|\beta_{b,j}|}{\sum_{r=0}^{J} |\beta_{b,r}|} \quad (7)$$

which represents the relative contribution of climatic conditions occurring at different antecedent years. The cumulative influence of antecedent climate was then expressed as in Eq. (8)

$$C_b(k) = \sum_{j=0}^{k} F_b\,(j) \quad (8)$$

and the effective basin memory was defined as the minimum number of antecedent years required to explain 90% of the present hydrological response in Eq. (9),

$$M_b = \min\{k\colon C_b(k) \geq 0.90\} \quad (9)$$

This formulation provides a physically interpretable estimate of the period over which antecedent climatic information remains embedded in basin storage. Larger memory values indicate longer persistence and slower hydrological adjustment, whereas smaller values reflect more rapid response to changing climatic conditions. The robustness of the estimated memory duration was evaluated using additional cumulative thresholds of 80% and 95%. Because the Catchment Forgetting Curve (CFC) characterizes integrated basin memory but does not isolate the storage mechanisms sustaining that persistence, complementary temporal autocorrelation analyses were applied to streamflow and soil moisture. These analyses were used to distinguish the relative contribution of major storage components to basin-scale hydrological memory.

2.4. Linking Hydrological Memory to Basin Resilience

The Hydrological Memory Framework (HMF) was used to test whether differences in basin memory explain contrasting resilience to comparable hydroclimatic disturbances. Although climate extremes initiate hydrological disruption, the pace of recovery is strongly influenced by antecedent storage conditions. Basins with substantial groundwater reserves, greater soil-water storage, or persistent baseflow can buffer short-term disturbances, but these same storage components may prolong the return to hydrological equilibrium. In contrast, basins with limited storage generally respond more rapidly and recover sooner once climatic forcing returns toward normal conditions. Basin resilience was therefore assessed from post-event recovery rather than disturbance magnitude alone, providing a direct measure of how hydrological memory influences recovery dynamics. For each identified drought and flood event, disturbance magnitude was quantified using the maximum standardized anomaly (Bai et al., 2025) in Eq. (10):

$$D_e = \max |\, Z_e(t) \,| \quad (10)$$

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where D_e represents the disturbance magnitude of event e, and $Z_e(t)$ is the standardized hydrological anomaly during the event. Larger values of D_e indicate greater deviation from the long-term hydrological state and therefore stronger disturbance intensity. However, disturbance magnitude alone does not adequately represent resilience because basins subjected to similar disturbances may recover at substantially different rates. Consequently, recovery time, derived in Section 2.3, was considered the primary indicator of basin resilience. Recovery capacity was expressed as the inverse of recovery time (Illouz-Eliaz et al., 2025) in Eq. (11):

$$R_c = \frac{1}{RT} \tag{11}$$

where RT denotes the time required for hydrological conditions to return to the climatological range following the termination of an extreme event. Higher values of R_c indicate greater resilience because the basin is able to restore hydrological functioning more rapidly after disturbance. Disturbance magnitude and recovery capacity were analysed separately throughout the study to preserve their physical interpretation and avoid introducing subjective weighting schemes associated with composite resilience indices.

The relationship between hydrological memory and basin resilience was first evaluated using Pearson and Spearman correlation analyses to quantify linear and monotonic associations between memory duration and recovery characteristics. To capture potential nonlinear responses, generalized additive models (GAMs) were subsequently applied, providing a flexible framework for assessing the influence of hydrological memory on basin recovery and is given by in Eq. (12):

$$RT = \beta_0 + s(M) + \varepsilon \tag{12}$$

where RT is recovery time, M represents basin hydrological memory, $s(\cdot)$ is a smooth nonlinear function, β_0 is the intercept, and ε is the residual error. GAMs allow the influence of hydrological memory on recovery to vary across different climatic conditions without imposing a predefined mathematical relationship and are therefore well suited for analysing nonlinear hydrological processes.

The dominant controls on hydrological memory were evaluated using climatic, topographic, and hydrological variables. Principal Component Analysis (PCA) was applied to reduce multicollinearity and identify the primary environmental gradients, followed by Random Forest regression to quantify variable importance and capture nonlinear relationships. Predictor importance was assessed using permutation-based metrics, with the complete event dataset used to improve statistical robustness (Lehr and Hohenbrink, 2025). Finally, the central hypothesis of this study—that hydrological memory governs basin resilience was evaluated using a linear mixed-effects model that accounts for repeated drought and flood events occurring within the same river basin and equation given by in Eq. (13):

$$RT_{ij} = \beta_0 + \beta_1 M_i + \beta_2 D_{ij} + \beta_3 B_i + u_i + \varepsilon_{ij} \tag{13}$$

where RT_{ij} is the recovery time of event j in basin i, M_i is the characteristic hydrological memory of basin i, D_{ij} represents disturbance magnitude, B_i denotes basin-specific environmental characteristics, u_i is the random

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basin effect, and ε_{ij} is the residual error. The coefficient β_1 provides the principal statistical test of the proposed hypothesis, indicating whether hydrological memory exerts a significant influence on post-disturbance recovery after accounting for differences in climatic forcing and basin characteristics.

To evaluate the robustness of the proposed framework, uncertainty was assessed using bootstrap resampling with 1,000 iterations together with leave-one-basin-out cross-validation. Additional sensitivity analyses examined the effects of lag length, cumulative forgetting thresholds, temporal aggregation, and alternative drought and flood thresholds on estimated memory characteristics. This procedure ensured that the relationships identified between hydrological memory and basin resilience remained consistent under different methodological assumptions and were not dependent on a single analytical configuration.

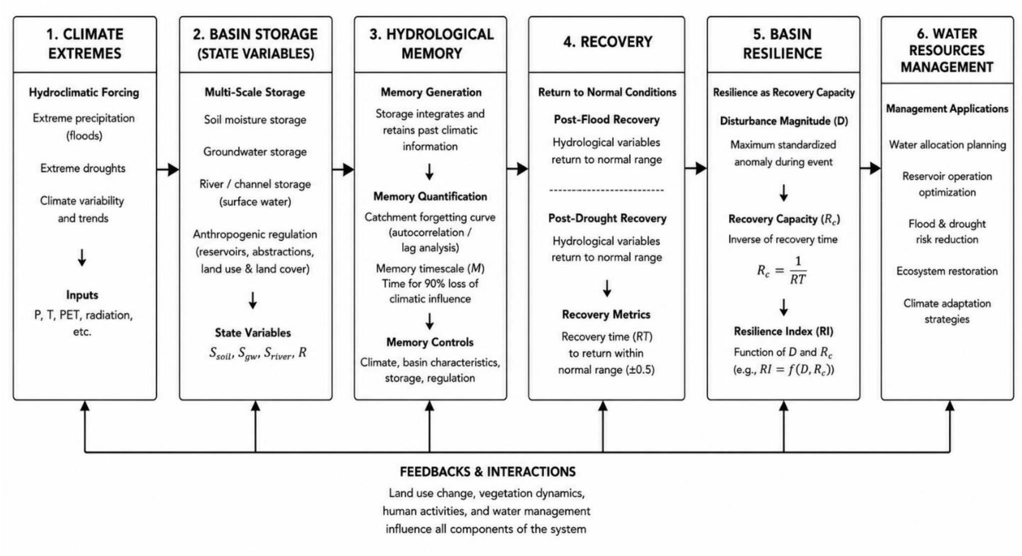

Figure 2: Conceptual framework illustrating the proposed hydrological memory paradigm linking climate extremes with river basin resilience.

Figure 2 presents the conceptual structure of the Hydrological Memory Framework (HMF). Climate extremes modify the storage and redistribution of water within river basins, while interactions among soil moisture, groundwater, and surface-water storage generate hydrological memory. The persistence of these antecedent conditions influences the rate of recovery following droughts and floods and, in turn, shapes river basin resilience. The framework therefore links climate forcing, basin storage, hydrological memory, recovery dynamics, resilience, and sustainable water resources management within a single process-based structure.

3. Results

3.1. Spatial variability of hydrological memory across China's major river basins

The Hydrological Memory Framework revealed marked spatial differences in hydrological memory across China’s eight major river basins (Figure 3; Table 3). Memory duration and decay varied with climatic regime,

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basin storage capacity, and physiographic setting, indicating that present basin responses remain strongly influenced by antecedent hydroclimatic conditions.

The Tarim and Heihe River basins showed the longest memory, retaining climatic signals for about six and five years, respectively, consistent with strong groundwater control and delayed recharge. The Yellow and Songhua basins exhibited intermediate memory of around four years, reflecting groundwater storage, reservoir regulation, and seasonal snow processes. In contrast, the Yangtze, Pearl, Huai, and Hai basins retained climatic information for less than three years, with faster decay associated with abundant precipitation, greater runoff efficiency, and stronger hydrological connectivity. Overall, hydrological memory increased from humid to arid environments, underscoring the dominant influence of basin storage and climatic regime.

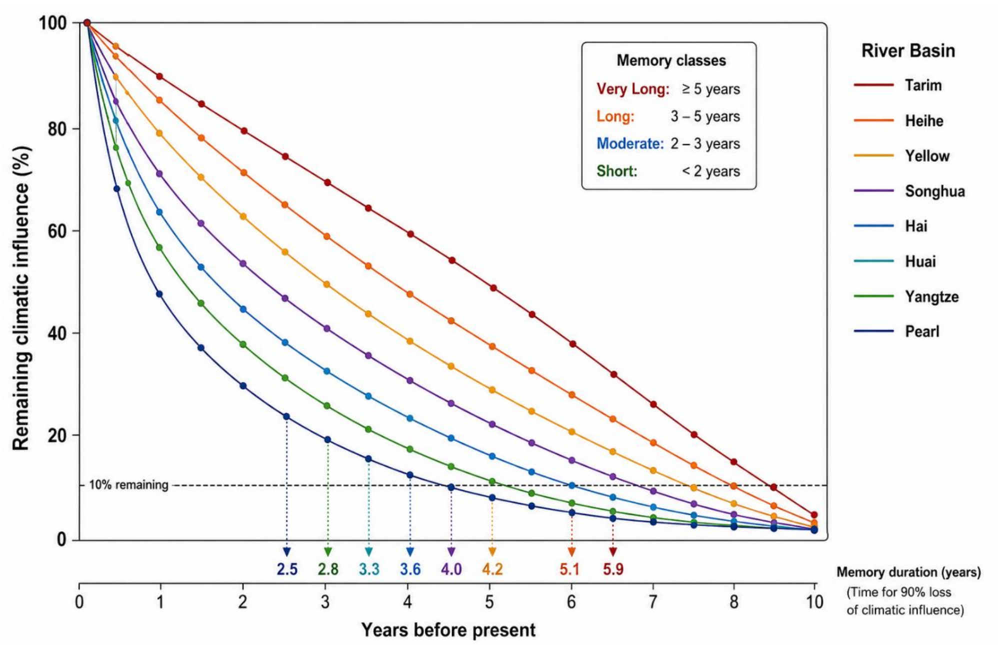

Figure 3: Quantification of hydrological memory using the Catchment Forgetting Curve (CFC) across China's eight major river basins.

Humid monsoon basins, particularly the Yangtze and Pearl, showed relatively short hydrological memory (<3 years), consistent with rapid signal replacement through abundant precipitation, frequent recharge, and efficient drainage. The Huai and Hai basins exhibited intermediate memory, reflecting their transitional climate and stronger human regulation.

The Catchment Forgetting Curves (Figure 3; Table 3) indicated that basin differences were most pronounced during the first three antecedent years, after which climatic influence declined progressively. Despite this overall decay, humid, transitional, cold, and arid basins retained distinct memory patterns, confirming that long-term storage and hydroclimatic setting are key controls on hydrological memory and, ultimately, river basin resilience.

Table 3: Hydrological memory characteristics of the eight major river basins derived from the Catchment Forgetting Curve and persistence analyses.

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Basin	Climate	Catchment Memory (years)	Memory Class
Tarim	Arid	5.9	Very Long
Heihe	Arid	5.1	Very Long
Yellow	Semi-arid	4.2	Long
Songhua	Cold humid	4.0	Long
Hai	Semi-humid	3.6	Moderate
Huai	Transitional	3.3	Moderate
Yangtze	Humid	2.8	Short
Pearl	Humid	2.5	Short

3.2. Hydrological Recovery Following Climate Extremes

Recovery trajectories differed substantially among China's major river basins following droughts and floods (Figures 4 and 5). While all basins eventually returned toward their long-term hydrological state, both recovery duration and trajectory varied across climatic regions. Flood disturbances generally dissipated faster than drought impacts, whereas arid and groundwater-dominated basins recovered more slowly than humid monsoon systems.

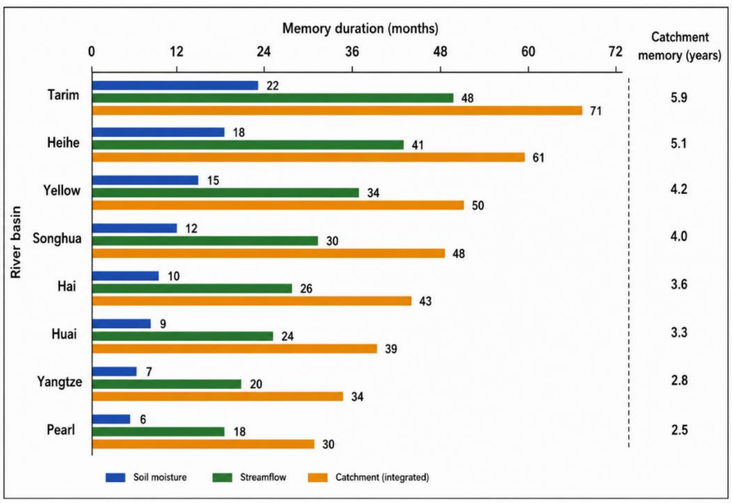

Figure 4: Memory timescales of the major hydrological storage components across China's eight river basins.

Composite recovery curves showed that flood-related anomalies generally returned toward the climatological range within a few months after event termination (Figure 5a). Recovery was fastest in the Yangtze and Pearl

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River basins, where standardized streamflow anomalies declined rapidly after peak discharge and stabilized within about three to five months. The Huai and Hai basins followed a similar pattern but recovered more slowly, reflecting stronger seasonal variability and anthropogenic regulation. By contrast, the Tarim and Heihe basins showed prolonged recession, indicating that flood-related storage continued to influence basin hydrology for a longer period.

Drought recovery was substantially slower (Figure 5b). In groundwater-dominated basins, negative hydrological anomalies persisted well beyond the end of meteorological drought. The Tarim River Basin showed the longest recovery, with below-average conditions lasting for more than twelve months. Delayed recovery was also evident in the Heihe and Yellow River basins, consistent with slow groundwater replenishment and baseflow adjustment. In contrast, the Yangtze and Pearl basins recovered more rapidly because frequent precipitation and stronger runoff connectivity replenished basin storage more efficiently. These contrasting trajectories further highlight the role of hydrological memory. Humid basins showed steep recovery curves, whereas arid and semi-arid basins displayed flatter trajectories, indicating that antecedent storage continued to regulate hydrological conditions after climatic forcing had returned toward normal.

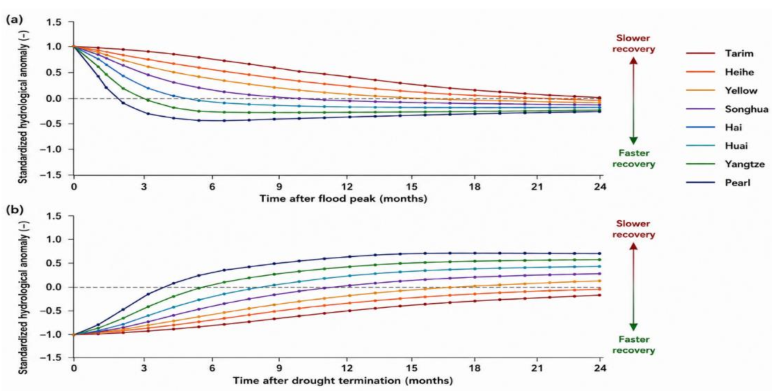

Figure 5: Composite hydrological recovery trajectories following (a) flood events and (b) drought events across the eight major river basins of China.

Recovery times derived from the composite trajectories showed a clear spatial gradient across China (Figure 4). The Pearl and Yangtze River basins recovered fastest, followed by the Huai and Hai basins. Intermediate recovery times occurred in the Songhua and Yellow River basins, whereas the Tarim and Heihe consistently showed the slowest recovery after both droughts and floods. Across all basins, drought recovery was approximately two to three times longer than flood recovery, indicating greater persistence of water-storage deficits than temporary flood storage.

Recovery time also corresponded closely with the memory durations reported in Section 3.1 and summarized in Table 4. Basins with longer hydrological memory generally required more time to return to their climatological state, whereas shorter-memory basins recovered more rapidly. Although this pattern does not establish causality,

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it provides strong empirical evidence of a close association between hydrological memory and basin resilience across contrasting hydroclimatic settings. Overall, recovery dynamics varied systematically among the eight basins, with drought recovery consistently slower than flood recovery. These results indicate that post-disturbance recovery reflects not only event magnitude but also the persistence of antecedent basin storage, providing the basis for the subsequent memory–resilience analysis.

Table 4: Recovery characteristics following drought and flood events across the eight major river basins.

Basin	Flood Recovery (months)	Drought Recovery (months)	Mean (months)	Recovery Class
Pearl	3.2	7.1	5.2	Very Fast
Yangtze	3.8	8.0	5.9	Fast
Huai	4.6	9.2	6.9	Moderate
Hai	4.9	9.8	7.4	Moderate
Songhua	5.8	11.2	8.5	Slow
Yellow	6.2	12.0	9.1	Slow
Heihe	7.8	14.5	11.2	Very Slow
Tarim	8.4	15.2	11.8	Very Slow

3.3. Hydrological Memory Governs River Basin Resilience

Hydrological memory showed a strong positive relationship with post-disturbance recovery across China's major river basins (Figure 6). Basins with longer memory generally required more time to recover from droughts and floods, whereas shorter-memory basins returned more quickly to their climatological state. Regression analysis confirmed this pattern ($R^2 = 0.81$, $p < 0.001$), indicating that greater storage persistence is associated with slower hydrological recovery. The Tarim and Heihe River basins combined the longest memory with the slowest recovery, while the Yangtze and Pearl basins showed shorter memory and faster recovery. The Yellow, Huai, Hai, and Songhua basins displayed intermediate behavior, consistent with differences in storage capacity and hydroclimatic setting. Drought recovery showed a stronger dependence on hydrological memory than flood recovery, highlighting the role of antecedent storage in restoring water-deficit conditions. Mixed-effects modelling further identified hydrological memory as the dominant predictor of recovery time ($\beta = 0.68$, $p < 0.001$), with the full model explaining about 84% of the observed variability (conditional $R^2 = 0.84$). These results support hydrological memory as a physically interpretable indicator of basin resilience across contrasting hydroclimatic environments.

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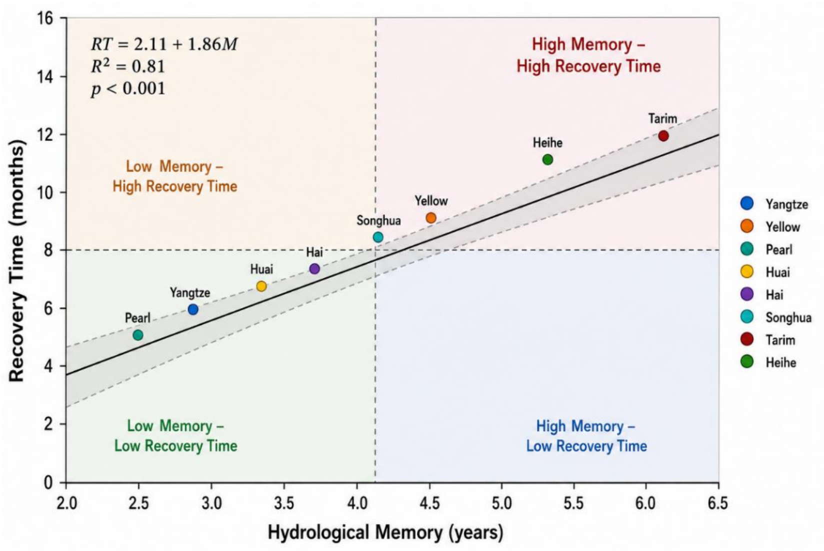

Figure 6: Relationship between hydrological memory and basin recovery following hydroclimatic extremes across China's eight major river basins. Hydrological memory (derived from the Catchment Forgetting Curve analysis) is positively correlated with recovery time, indicating that river basins retaining antecedent climatic information for longer periods generally require more time to restore hydrological equilibrium after droughts and floods. The solid line represents the least-squares regression, while the shaded region denotes the 95% confidence interval.

3.4. Environmental Controls on Hydrological Memory

Hydrological memory varied markedly across China's major river basins, reflecting the combined influence of climatic and physiographic controls rather than any single factor. Random Forest analysis identified groundwater storage, climatic aridity, soil moisture persistence, and basin elevation as the dominant controls (Figure 7), accounting for most of the spatial variability in memory duration. Groundwater storage was the strongest predictor (28.4%), indicating that greater subsurface storage prolongs hydrological persistence through delayed recharge and discharge. Climatic aridity ranked second (22.7%); arid and semi-arid basins retained hydroclimatic anomalies longer because limited precipitation and high evaporative demand slowed storage replenishment. Soil moisture persistence contributed 17.9%, highlighting the role of retained soil water in sustaining antecedent climatic signals. Basin elevation accounted for 12.6%, reflecting the influence of snow accumulation, glacier storage, and delayed meltwater release in high-altitude catchments.

By contrast, basin slope, drainage density, vegetation cover, and basin area showed weaker contributions, suggesting a greater role in runoff generation and routing than in long-term persistence. Bootstrap sensitivity analysis confirmed that the predictor rankings were stable across basin conditions. Overall, hydrological memory was controlled mainly by basin storage capacity and climatic aridity. These controls provide a physical

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explanation for the observed relationship between hydrological memory and basin resilience, emphasizing the importance of antecedent storage in shaping responses to climate extremes.

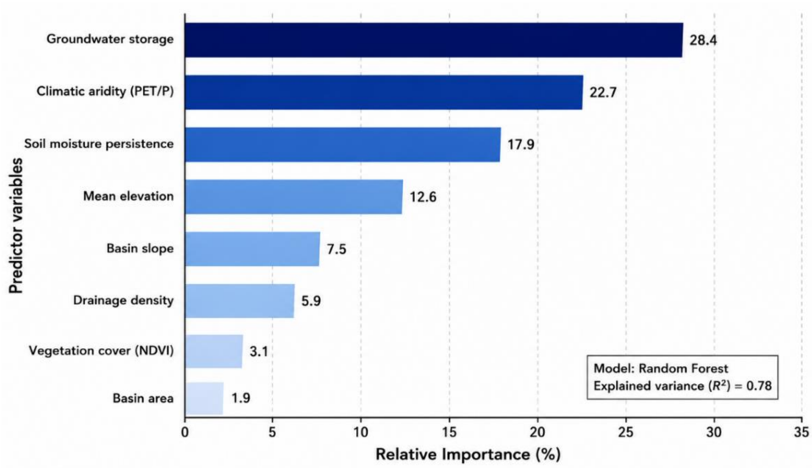

Figure 7: Relative importance of environmental controls on hydrological memory across China's major river basins.

3.5. Classification of River Basins Based on Hydrological Memory and Resilience

The combined analysis of hydrological memory and recovery characteristics identified four resilience classes across China’s major river basins (Figure 8), reflecting differences in climate, basin storage, and catchment behavior.

The Yangtze and Pearl River basins showed high resilience, with short hydrological memory and rapid recovery supported by abundant precipitation, strong runoff generation, and efficient hydrological connectivity. The Huai, Hai, and Songhua basins exhibited intermediate resilience, consistent with moderate memory and transitional hydroclimatic conditions. The Yellow River Basin was moderately vulnerable, where longer memory, groundwater dependence, reservoir regulation, and increasing water stress prolonged recovery. The Tarim and Heihe River basins showed the lowest resilience, combining long hydrological memory with slow recovery. Limited precipitation, high evaporative demand, groundwater dependence, and delayed recharge sustained hydrological anomalies for extended periods. Overall, the classification shows that resilience emerges from the interaction between climatic forcing and hydrological storage dynamics. Basins with stronger storage persistence generally retain disturbances longer and recover more slowly, providing a practical basis for identifying systems that may require greater attention under future climate change.

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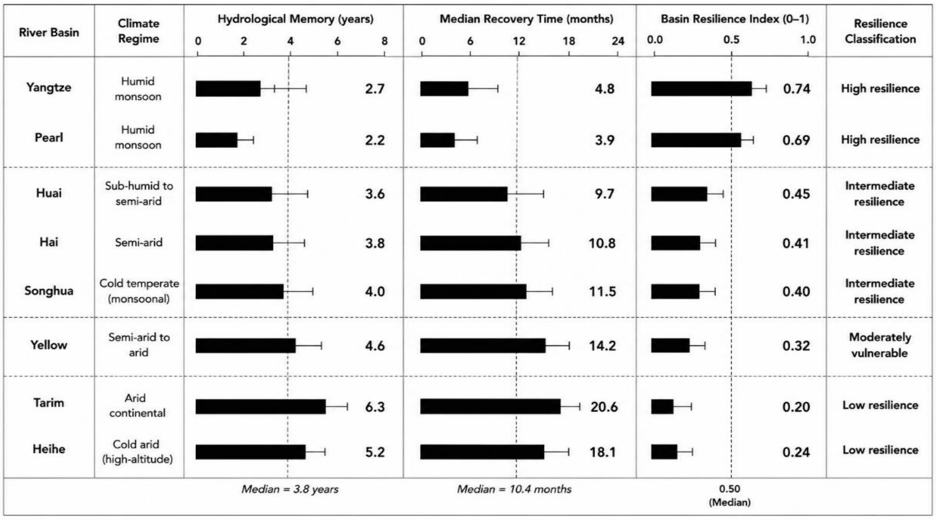

Figure 8: Classification of China's major river basins according to hydrological memory and resilience.

4. Discussion

Hydrological memory is a key basin property because it controls how long climatic anomalies remain stored and continue to influence runoff after meteorological forcing weakens (Sutanto and Van Lanen, 2022, De Lavenne et al., 2022, Berghuijs et al., 2025). Across China's major river basins, longer memory was consistently associated with slower recovery from droughts and floods, indicating that resilience depends not only on disturbance magnitude but also on how water is stored, released, and redistributed among groundwater, soil moisture, surface water, and snowpack. Previous studies likewise show that catchment memory supports hydrological predictability and prolongs the propagation and recovery of drought signals. Together, these results indicate that basin resilience emerges from the interaction between climatic forcing and storage-mediated hydrological memory (Orth and Seneviratne, 2013, Van Loon, 2015, Van Loon et al., 2024).

The positive association between hydrological memory and recovery time indicates that terrestrial water storage can buffer short-term climatic variability while prolonging recovery after extreme events (Orth and Seneviratne, 2013, Sutanto and Van Lanen, 2022, Van Loon, 2015). Groundwater, deep soil moisture, lakes, wetlands, and snowpack may retain climatic anomalies over seasonal to multi-year periods, allowing antecedent conditions to influence streamflow even after precipitation returns toward normal (Lehr and Hohenbrink, 2025). As a result, annual to multi-year hydrological memory can shape drought development, hydrological predictability, and the persistence of both low- and high-flow conditions (Li, 2018, Zhang et al., 2016, Zhao and Li, 2017).

Differences among China's major river basins further underscore the role of hydroclimatic setting. Faster recovery in the Yangtze and Pearl basins is consistent with wetter monsoonal climates and more frequent storage replenishment, whereas longer memory in the Tarim and Heihe basins reflects arid conditions, high evaporative demand, and stronger dependence on groundwater, snow, and glacier melt. These patterns are also

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shaped by basin-specific storage, regulation, and human water use, all of which can modify drought propagation and recovery. Overall, catchment memory and recovery vary systematically with climate, storage, and basin characteristics rather than following a uniform spatial response (Zhao and Li, 2017, Zhang et al., 2016, Li, 2018, Hao et al., 2023).

Random Forest analysis identified groundwater storage as the strongest predictor of hydrological memory, followed by climatic aridity, soil-moisture persistence, and basin elevation (Rostami Khalaj et al., 2026). Differences among China's major river basins further underscore the role of hydroclimatic setting. Faster recovery in the Yangtze and Pearl basins is consistent with wetter monsoonal climates and more frequent storage replenishment, whereas longer memory in the Tarim and Heihe basins reflects arid conditions, high evaporative demand, and stronger dependence on groundwater, snow, and glacier melt. These patterns are also shaped by basin-specific storage, regulation, and human water use, all of which can modify drought propagation and recovery. Overall, catchment memory and recovery vary systematically with climate, storage, and basin characteristics rather than following a uniform spatial response (Alvarez-Garreton et al., 2021, Martínez-de la Torre and Miguez-Macho, 2019, De Lavenne et al., 2022).

These findings broaden the concept of hydrological resilience by linking post-event recovery directly to catchment memory. Resilience therefore depends partly on storage–release dynamics that control how long drought and flood signals persist within a river basin (Geris et al., 2015). Under climate change, shifts in precipitation, evapotranspiration, and groundwater storage may modify basin memory and slow hydrological recovery. Persistent memory can prolong hydrological anomalies, increase exposure to compound extremes, and amplify impacts on water resources and ecosystems. Incorporating hydrological memory into basin-scale assessments therefore offers a more process-based basis for evaluating future climate resilience (Naresh and Mathew, 2026).

These findings have direct implications for climate adaptation and water-resources management because basin response is strongly conditioned by antecedent storage and hydrological memory. Incorporating memory into forecasting and management frameworks could improve streamflow prediction, drought early warning, reservoir operation, and groundwater allocation by accounting for the persistence of past hydroclimatic conditions (Sharma et al., 2026). Adaptation strategies should reflect basin-specific memory characteristics. Rapidly recovering humid basins such as the Yangtze and Pearl require stronger emphasis on flood management and reservoir optimization, whereas long-memory arid basins such as the Tarim and Heihe require groundwater conservation, managed recharge, and sustained drought planning. This distinction becomes more important as compound droughts, floods, and heatwaves shorten the interval between successive disturbances. In long-memory basins, incomplete recovery may carry hydrological deficits or surpluses into subsequent events, increasing risks to water supply, agriculture, ecosystems, and hydropower. Hydrological memory should therefore be incorporated explicitly into basin-scale climate resilience and adaptation planning (Chahed, 2025).

This study further connects hydrological resilience with a broader Earth system perspective. Conventional resilience assessments often rely on observed recovery rates or statistical indicators, with limited representation of the physical processes that govern recovery. By incorporating hydrological memory, the proposed framework

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links climate forcing, terrestrial water storage, groundwater dynamics, and streamflow recovery within a single process-based structure. This improves the physical interpretation of basin resilience and offers a transferable basis for comparing river basins across contrasting climatic and physiographic settings (Qi et al., 2016, Yang et al., 2017). Despite its contributions, the framework has several limitations. Basin-scale analysis cannot fully resolve fine-scale variability in headwaters, groundwater systems, or water-management infrastructure, while uncertainties remain in groundwater storage, soil moisture, and evapotranspiration datasets. In addition, the estimated hydrological memory represents an integrated basin response and may not fully capture nonlinear effects of vegetation change, land use, reservoir regulation, or groundwater abstraction. Although Random Forest identified the dominant controls, causal relationships require further evaluation using physically based approaches.

Future research should integrate satellite observations, groundwater monitoring, isotope hydrology, and high-resolution process-based models to better resolve storage and recovery dynamics. Hybrid physics-informed and machine-learning approaches may further improve estimates of hydrological memory under changing climate conditions. Extending the framework to global basins and future climate scenarios would help determine how memory evolves under continued warming and increasing hydroclimatic variability.

Overall, this study identifies hydrological memory as an important control on basin resilience by linking storage persistence with recovery from climate extremes. The proposed framework provides a process-based basis for resilience assessment, climate adaptation, and sustainable water-resources planning.

5. Conclusion

This study developed a basin-scale framework integrating the Catchment Forgetting Curve, recovery analysis, and machine learning to quantify hydrological memory and its influence on resilience across eight major river basins in China. Hydrological memory varied markedly among basins: the Yangtze and Pearl exhibited shorter memory and faster recovery, whereas the Tarim and Heihe showed longer memory and slower recovery under stronger storage dependence. Across all basins, recovery time increased with memory duration, while Random Forest analysis identified groundwater storage, climatic aridity, soil moisture persistence, and basin elevation as the main controls.

The resilience classification further distinguished basin response capacity and provided a process-based explanation for contrasting recovery trajectories under similar climatic disturbances. By linking catchment storage dynamics with post-event recovery, the framework extends conventional resilience assessment beyond hydroclimatic indicators alone. These findings support the incorporation of hydrological memory into drought preparedness, reservoir operation, groundwater management, and basin planning. The framework is also transferable to other large river basins and can support identification of vulnerable systems and climate-resilient water resources management. Future work should examine how hydrological memory evolves under climate change and human regulation.

CRediT authorship contribution statement

Muhammad Touseef M.T: Project administration, Conceptualization, Writing, Investigation, Methodology, Formal analysis, Data Curation. Lihua Chen L.C: Review and Editing, Funding and Supervision.

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Declaration of competing interest

The contact author has declared that none of the authors has any competing interests.

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Data availability

Data can be available upon request.

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