https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

Streamflow analyses reveal significant subsurface-mediated hydrological effects of dams upstream and in adjacent catchments

Darrell W. S. Tang[1,2], Xiaoyan Song[1*], Bjørn Kløve[2]

1. College of Water Resources and Architectural Engineering, Northwest A&F University, Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Yangling, Shaanxi 712100, China

2. Water, Energy, and Environmental Engineering, University of Oulu, Finland

Corresponding Author: Xiaoyan Song (xiaoyansong@nwsuaf.edu.cn)

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.



Abstract

In regulated streams, the presence of dams and reservoirs often dominates over climate change in controlling downstream hydrological processes. However, the relative influence of hydraulic infrastructure on hydrological processes at non-downstream locations remains sparsely understood. With the Hunter River Basin as case study, we develop a methodology to separate and quantify dam and climate change effects on downstream and nearby non-downstream streamflow fluxes and persistence, using simulations of naturalized catchment hydrological processes in SIMHYD. Framework validity and physical interpretation are supported by comparative analyses against two classical change attribution methods: the elasticity and double mass curve methods. Results show that climate change decreased streamflow persistence similarly throughout, but had diverse location-dependent effects on mean streamflow. Dam impacts increased with the size of the reservoir they impound. Dams reduced mean streamflow with similar or greater magnitudes upstream and in adjacent catchments, compared to near-downstream locations. Dams increased streamflow persistence strongly near-downstream, but with intermediate strength at nearby non-downstream locations, and weakly far-downstream. Therefore, dam effects on mean streamflow and streamflow persistence in nearby areas not intentionally regulated may be larger than regulated reaches farther downstream, mediated by subsurface hydraulic interactions that alter evapotranspiration and baseflow. Furthermore, of the total effects, relative contributions of dams to shifts in mean streamflow (64% average) and streamflow persistence (55% average) were uncorrelated across locations. These findings underscore the complementarity of analyzing streamflow persistence with catchment water balances for hydrologic change attribution, and their value towards anticipatory water management and targeted mitigation of floods and droughts.

Keywords

Hydraulic infrastructure; dams and reservoirs; upstream; streamflow persistence; hydrological change attribution

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

1. Introduction

Obtaining and maintaining sufficient access to quality water resources to sustain society and the environment, while avoiding and mitigating destructive events such as floods and droughts, is a fundamental objective of water resource management. A major challenge is that the drivers of hydrological processes and hydrological change are highly variable at a global scale due to the myriads of regional geographical characteristics, land-use types, water consumption behavior, and other human activities (Vogel et al., 2015). Climate change is now known to be a common cause of exacerbated water stress and hydrological variability worldwide (Xiong & Yang, 2024; Rosa & Sangiorgio, 2025). However, the effects of climate change on the hydrological cycle are highly uncertain (Zhang et al., 2026). Furthermore, climate change occurs concurrently with changes related to human activity, including land-use change, agricultural intensification, and hydraulic infrastructure construction, which may have local effects exceeding those of global climate change (Kåresdotter et al., 2022). Hence, a prerequisite for accurately characterizing the effects of climate change on hydrological processes, is to be able to separate the impacts of climate change from the impacts of other human activity (Brunner et al., 2021). This has been the focus of a large body of literature on hydrological impact separation and change attribution in various environmental contexts (Dey & Mishra, 2017).

The effects of human activity on hydrological change are particularly prominent in regulated streams. Within regulated streams, hydraulic infrastructure such as canals, dams, hydropower, or extensive irrigation networks typically dominate downstream hydrological regimes (Singh & Basu, 2022). At present, the literature on the effects of dams on catchment hydrology primarily focuses on downstream effects, as dam operation is primarily intended to regulate downstream water availability. However, since hydraulic pressure can propagate against gravity and topography, dam reservoirs will also affect streamflow in the streamflow gauges that are not directly downstream of a dam (Wang et al., 2026). Within the surface water, backwater effects may be propagated upstream, while hydraulic interactions at confluences of major regulated streams cause backwater effects to propagate upwards into adjacent unimpaired streams (Meng et al., 2025; Zhan et al., 2025). Within the subsurface, hydrostatic pressures caused by water stored in dam reservoirs can affect groundwater exchange, groundwater levels, and soil moisture upstream of dams or in adjacent catchments (Le Moine et al., 2007). These hydraulic interactions in turn can affect long-term water balances by increasing evapotranspiration and subsurface water storage. Although large-scale descriptions of hydrological regime changes at continental and global scales are available in the literature, covering locations

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

both downstream and non-downstream of dams, such large-scale studies lack the spatial resolution and mechanistic modeling needed to separate the influences of dams and climate change on local hydrological regime changes. Hence, the effects of dams on non-downstream streamflow fluxes and variability in the vicinity, and their relative dominance compared to climate change effects, remain relatively poorly understood.

Hydrologic change attribution studies, aimed at separating the hydrological effects of climate change and other human activity, can yield valuable insight for land-use and water resources management. For example, climate change was found responsible for 88% of changes to long-term mean streamflow in the Goulburn river catchment of Australia, and mining activity for the remaining minor portion of 12% (Song et al., 2020). In some cases, human activity may have relatively severe impacts, such as being responsible for up to half of the streamflow deficit observed during a decade-long megadrought in Chile (Álamos et al., 2023). Moreover, by estimating how human activity and climate change individually affect streamflow across different periods of time, the severity and duration of human-induced floods or droughts (i.e., floods or droughts that would not have occurred if the human activity did not occur) can be assessed (Van Loon et al., 2022). From such an analysis, Van Loon et al (2022) showed that the streamflow-increasing effects of impervious urban land-use may be counteracted by sewage return flows, and that reduced subsurface moisture depletion due to deforestation for agriculture may be counteracted by increased agricultural groundwater abstraction. Such underlying mechanisms would be missed if the effects of various drivers of hydrological regime shifts were not separated.

Existing studies on hydrological change attribution have mostly focused on how various drivers of hydrological change have affected the mean streamflow. In addition to the mean streamflow, climate change and human activity also affect the temporal variability of hydrological fluxes (Xiong & Yang, 2024). Hao et al (2024) showed that although irrigation and water abstraction reduced long-term mean streamflow in the Yellow River Basin of China by 2%-6%, it decreased the intensity of extreme flood peaks by up to 35%, thereby effectively attenuating the temporal variability of streamflow. Therefore, the temporal variability may be more crucial than the mean streamflow in issues such as floods, groundwater pollution, and agricultural drought risks, where the greatest hazards may be caused by intermittent acute events rather than the long-term average behavior (Zhou et al., 2023; Tang et al., 2024a). Therefore, hydrologic change attribution should also be performed on streamflow variability, in addition to mean streamflow, to obtain more comprehensive insights into the hydrologic consequences of human activity.

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

Accordingly, one objective of this study is to characterize the individual effects of dams and climate change on hydrological regime shifts between pre- and post-dam construction periods, comparing downstream and non-downstream locations such as upstream and in adjacent unregulated catchments. Moreover, a framework is developed to separate the effects of dams and climate change on streamflow fluxes and streamflow variability, two key aspects of regional hydrological characteristics. Hence, the main objectives and novelties of this study pertain to (1) the non-downstream hydrologic change attribution for dams, and (2) a new methodology that considers streamflow variability in addition to mean fluxes for hydrologic change attribution. Each main objective enables a more comprehensive process-based interpretation of the other. The Hunter River Basin (HRB) on the east coast of Australia is chosen as a case study area due to the availability of streamflow gauges downstream, upstream, and in nonregulated catchments adjacent to major dam projects, along with long streamflow data records.

2 Methods

2.1 Study area

The HRB is a highly flood-prone catchment that has been the target of intensive flood mitigation efforts, and has transitioned between a highly natural and highly managed state within the past century (Spink et al., 2009; Rustomji et al., 2009). The construction of dams and reservoirs impounded by the dams has led to hydrologic regime shifts in the region. Although water extraction for domestic, agricultural, and industrial uses affects streamflow in the area, the impact on catchment fluxes and water balances is minimal due to small permissible extraction limits (<0.05 mm/d) and sparse settlement (Zhang et al., 2016), implying that hydrologic shifts here would be caused primarily by dams and their impounded reservoirs. Regulated streams in the HRB are the Hunter River beneath the Glenbawn Dam, Glennies Creek beneath the Glennies Creek Dam, and the Paterson River beneath the Lostock Dam (Figure 1). The latter two are tributaries of the Hunter River. These streams are regulated by large dams to maintain stable flows and prevent excessively low flows, as they supply population centers and extensive agricultural activity downstream (Quinn, 2011). Each dam regulates outflows from water reservoirs that it impounds. The Glenbawn reservoir and Glennies Creek reservoir have substantial water storage capacities, whereas the Lostock reservoir is comparatively small relative to catchment size (Table 1).

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.



158

159 Figure 1: *Map of the Hunter River Catchment, with the seven streamflow gauges marked*
160 *with black circles (adapted from an original map provided by the New South Wales*
161 *Environment Protection Authority, CC BY 4.0). Black circles indicate the seven studied*
162 *gauges.*

163

164

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

Table 1: Observed streamflow gauges, their characteristics, and the three time periods of interest: pre-dam, change point, and post-dam. Data obtained from NSW Government (2006) and Zhang et al (2016).

Station number	Streamflow gauge station	Catchment area [km^2]	Location relative to dam	Pre-dam observation period	Dam construction period	Post-dam observation period	Dam reservoir capacity [GL]
210014	Rouchel Brook at The Vale	395	Adjacent unimpaired stream	1940-1947	1948-1958	1959-2012	749
210015	Hunter River at Glenbawn Dam	1295	Near downstream of large dam		Glenbawn Dam		
210018	Hunter River at Moonan Damsite	764	Near upstream of large dam				
210021	Paterson River at Lostock Dam	277	Near downstream of small dam	1941-1958	1969-1971	1972-2012	20
210022	Allyn River at Halton	205	Adjacent unimpaired stream		Lostock Dam		
210044	Glennies Creek at Middle Falbrook	466	Far downstream of large dam	1969-1979	1980-1983	1984-2012	282
210084	Glennies Creek at the Rocks	227	Near downstream of large dam		Glennies Creek Dam		

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

The HRB has a well-documented history of hydraulic infrastructure interventions, and availability of historical hydrological data stretching back to periods with natural hydrological regimes. We analyze in detail multiple decades of daily streamflow records at seven gauge stations spanning three sub-catchments with different positions relative to dams of different sizes (Table 1; Figure 1). The seven stations span three sub-catchments of the HRB. Four stations (210015, 210021, 210044, 210084) are located either near downstream or far downstream of a dam. Nearby stations that are not downstream of a dam are also studied: station 210018 upstream (<10 km) of the Glenbawn Dam, and stations 210014 and 210022 in unimpaired catchments close (<10 km) to a dam (Peel et al., 2000). Gauge stations, sub-catchments, and time periods with contrasting hydrological controls are compared, so that the underlying hydrological processes can be characterized in a more physically intuitive and comprehensive manner, which allows for comparative hydrological analyses of the impacts of the hydraulic infrastructure (Gaál et al., 2012; Singh et al., 2014).

2.2 Methodological framework

An overview of the methodological framework of this study is as follows. Daily streamflow records of the pre-dam period from the seven stations in study area are used to calibrate the hydrological process model SIMHYD at a daily temporal resolution. These pre-dam calibrated models represent the naturalized hydrological conditions, absent of dams and reservoirs, of the study area. The simulated naturalized streamflow from the post-dam period are then compared with actual observed post-dam streamflow records, to reveal hydrological regime shifts between the pre-dam and post-dam periods. The calibrated SIMHYD model, along with two classical methods of mean streamflow change attribution (elasticity method and double mass curve method), are used to distinguish the individual contributions of the dams and climate change to changes in mean streamflow between the pre-dam and post-dam periods. Having shown that the calibrated SIMHYD model attributes mean streamflow changes consistently with the two classical methods, we then use the calibrated SIMHYD model to distinguish the individual contributions of the dams and climate change to shifts in an indicator of streamflow variability, the Hurst exponent. Finally, by showing that the estimated individual effects of dams and climate change on each metric (mean streamflow and Hurst exponent) sum up approximately to the total change in each metric between the pre-dam and post-dam periods, we show empirically that that the change in Hurst exponent can be first-order decomposed into the individual contributions of dams and climate change. This then affirms that the Hurst exponent is an

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

appropriate and informative metric of streamflow variability for hydrologic change attribution studies, and that the methodological framework yields meaningful results.

2.3 The Hurst exponent as an indicator of streamflow variability

When the average streamflow within a catchment is calculated over increasingly larger time windows, the average converges towards a stable value determined by the average atmospheric forcing absent anthropogenic intervention (Kirchner & Neal, 2013). This follows from the water balance principle: there is minimal long-term change to water storage within a catchment, thus all deposited rainfall either leaves a catchment through streamflow or evapotranspiration on a long-term average (Wang & Hejazi, 2011). However, at smaller time scales, the average streamflow depends on the size of the averaging time window because of water storage fluctuations in groundwater, snow, ice, and soil moisture. Thus, as the averaging time window enlarges, the convergence of the mean streamflow to a stable value is slower than expected under a white noise process with convergence rate described by the central limit theorem, due to the terrestrial system's long-term memory of past states (O'Connell et al., 2016). This is the Hurst phenomenon, which describes long-term persistence in streamflow timeseries (Pizarro et al., 2024). For processes that obey the Hurst phenomenon, as the observation time window enlarges, the outcome timeseries (e.g, streamflow) is described by $\sigma_N \propto N^{H-1}$, where σ_N is the standard deviation of the means of N-length subsamples, and H is the Hurst exponent (O'Connell et al., 2016). A system with $H = 0.5$ exhibits white noise behavior (low persistence, relatively high variability), larger values of $H > 0.5$ imply increasing long-term persistence and memory effects, and $H = 1$ describes random walk processes with strong temporal autocorrelations (high persistence, indicating low variability).

The Hurst phenomenon is a powerful conceptual framework with a clear physical interpretation (Pizarro et al., 2024). Since streamflow is ultimately driven by atmospheric forcing, and since terrestrial water storage merely buffers the response of streamflow to atmospheric forcing by introducing a delay, long-term persistence in streamflow and in atmospheric forcing are mechanistically related (O'Connell et al., 2022; Hurst, 1951). The effects of climate change on precipitation variability and evapotranspiration variability are reflected in the surface water fluxes (Hansford et al., 2020; O'Connell et al., 2023), which can be separated from the impacts of human activity. Unlike classical frequentist statistics, the Hurst phenomenon characterizes the natural scale-dependent variability of hydroclimatic processes that would occur even without global climate change, hence

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

enabling climate change induced shifts to be more clearly identified (Koutsoyiannis, 2003). Moreover, the Hurst phenomenon relates the expected variability in streamflow to the time horizon in consideration, over time scales spanning multiple orders of magnitude (Markonis et al., 2018; O'Connell et al., 2023). This is informative for anticipatory water management, flood adaptation, and agricultural drought mitigation, especially in catchments with short data records (O'Connell et al., 2022). Characterizing streamflow variability through the extent of its long-term persistence is especially important for anticipatory water management because it contrasts directly with the mean-regressing behavior expected under classical frequentist statistics. This is because the most severe consequences of hydrological disasters often occur under continuous or successive unfavorable conditions, such as where drought follows drought or flood follows flood (O'Connell et al., 2022). Therefore, the Hurst exponent H is proposed as a meaningful and indicator of streamflow variability for water management, that is information-dense despite not covering all aspects of streamflow variability that may be of interest.

2.4 Hydrological process simulations

Daily precipitation, potential evapotranspiration, and streamflow data at the streamflow gauges and periods, periods of dam construction, and the properties of dams and reservoirs specified in Table 1, were obtained from the New South Wales Office of Water and the SILO Australian climate database. Hurst exponent H values were calculated with the rescaled range analysis algorithm, which is appropriate and robust for analyses of hydrometeorological timeseries (Rao & Bhattacharya, 1999; Szolgayova et al., 2012; Zhang et al., 2024). Hydrological process simulations were performed using the SIMHYD with routing model, which was designed with a focus on Australian hydrological conditions (Chiew et al., 2002; Pool et al., 2024). SIMHYD takes precipitation and potential evapotranspiration data as input, and partitions precipitation entering the catchment into green water fluxes (actual evapotranspiration including canopy interception) and blue water fluxes including surface runoff, interflow, baseflow, and streamflow discharge. All fluxes, including the precipitation P, potential evapotranspiration data E_0, and streamflow Q, are reported as mean daily values of the relevant time periods (pre-dam or post-dam).

Calibration of the SIMHYD model was performed for each streamflow gauge, using the full period of pre-dam data to achieve robust calibration (Shen et al., 2022). The SIMHYD models received inputs of precipitation and potential evapotranspiration data, and were calibrated against the streamflow data by genetic algorithm (population size: 300,

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

maximum generations: 100) using the objective function $KGE(Q) + NSE(\log Q)$, to obtain a balance between the accurate characterization of water balances and persistence with $KGE(Q)$ and extreme flow behavior with $NSE(\log Q)$ (Araya et al., 2023). Here, KGE is the Kling-Gupta efficiency and NSE is the Nash-Sutcliffe efficiency. A warmup period of one year was used, thus the first 365 days of observations from each calibration attempt were excluded from the objective function and the simulated outcomes (Srikanthan et al., 2025).

The contributions of climate change to mean streamflow $\Delta Q_{c,sim}$ and streamflow persistence $\Delta H_{Qc,sim}$ were calculated by taking the differences between the pre-dam SIMHYD simulations and post-dam naturalized simulations (i.e., using pre-dam parameter values and post-dam atmospheric forcing data) (Terrier et al., 2021). The contributions of human activity to mean streamflow ΔQ_h and streamflow persistence $\Delta H_{Q,h}$ are then calculated by subtracting $\Delta Q_{c,sim}$ and $\Delta H_{Qc,sim}$ from the total observed changes ΔQ and ΔH_Q respectively. The partial impacts of human activity on streamflow averages F_Q and streamflow persistence F_H, relative to the total combined impacts of human activity and climate change, are

$$F_Q = \frac{\Delta Q_h}{|\Delta Q_h| + |\Delta Q_c|} \quad (1)$$

$$F_H = \frac{\Delta H_{Qh}}{|\Delta H_{Qh}| + |\Delta H_{Qc}|} \quad (2)$$

Therefore, for hydrologic change attribution analyses, calibrating SIMHYD to pre-dam catchment characteristics is sufficient, and calibration to the post-dam catchment characteristics is not necessary. Nevertheless, we also additionally calibrated SIMHYD to post-dam conditions to calculate $\Delta Q_{h,sim}$ and $\Delta H_{Qh,sim}$, by subtracting the outputs of post-dam naturalized simulations from the post-dam calibrated simulations. This was done to perform an additional check that the SIMHYD simulations were reasonable, by showing that the expected outcome $\Delta Q \sim \Delta Q_{c,sim} + \Delta Q_{h,sim}$ holds. For another additional check of model rationality, the SIMHYD simulations were compared against two other widely used hydrological change attribution methods: (1) the Budyko elasticity method based on the Mezentsev Budyko curve, and (2) the double mass curve method (DMC).

2.5 The double mass curve method

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

With the double mass curve method (DMC) (Gao et al., 2017), the best-fit line between the cumulative precipitation and cumulative streamflow is regressed from pre-dam data. Then, the gradient of the best-fit line is multiplied by ΔP (the difference in observed pre-dam and post-dam mean daily precipitation) to obtain the climate change contribution to mean daily streamflow change $\Delta Q_{c,dmc}$. The contribution of human activity is then calculated as $\Delta Q_{h,dmc} = \Delta Q - \Delta Q_{c,dmc}$. This is a simple method with no parameters, and thus can provide basic insight free from potential parameterization or calibration errors.

2.6 The Budyko elasticity method

The Budyko elasticity method with the Mezentsev-Budyko curve was also applied to a standard elasticity analysis of the response of streamflow Q to changes in the catchment's aridity index E_0/P, yielding the climate change contribution to streamflow change $\Delta Q_{c,bud}$. Amongst the Budyko-type curves, the Mezentsev curve was chosen because it is physically sound, and amenable to mathematical analysis (Zhou et al., 2015). The parameter value for the alternative Fu-Budyko curve is approximately 2.79 in the study area (Teng et al., 2012), which is equivalent to a parameter value of n=2.1 for the Mezentsev-Budyko curve used in this study (Yang et al., 2008). The Mezentsev-Budyko curve is given by

$$\frac{E}{P} = \left[1 + \left(\frac{E_0}{P}\right)^{-n}\right]^{-\frac{1}{n}} \tag{3}$$

and the elasticity coefficients for precipitation m_p and potential evapotranspiration m_e are

$$m_p = \frac{\frac{\partial E}{E}}{\frac{\partial P}{P}} = \frac{g}{g+1} \tag{4}$$

$$m_e = \frac{\frac{\partial E}{E}}{\frac{\partial E_0}{E_0}} = 1 - m_p \tag{5}$$

$$g = \left(\frac{E_0}{P}\right)^n \tag{6}$$

Following from the assumptions that no changes to terrestrial water storage occurs on average in the long term, and that the resulting long-term water balance terms are $P = E + Q$, the climate change contribution to mean streamflow change $\Delta Q_{c,bud}$ can be calculated by adding together the partial responses of streamflow to shifts in precipitation and potential evapotranspiration (Zhou et al., 2015)

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

$$\frac{\partial Q}{\partial P} = \frac{\partial (P - E)}{\partial P} = 1 - \frac{\partial E}{\partial P} \tag{7}$$

$$\frac{\partial Q}{\partial E_0} = \frac{\partial (P - E)}{\partial E_0} = -\frac{\partial E}{\partial E_0} \tag{8}$$

$$\Delta Q_{c,bud} = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial E_0}\Delta E_0 = \left(1 - \frac{m_p P}{P - Q}\right)\Delta P - \left(\frac{m_e E_0}{P - Q}\right)\Delta E_0 \tag{9}$$

The contribution of human activity is calculated as $\Delta Q_{h,bud} = \Delta Q - \Delta Q_{c,bud}$.

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

3. Results

3.1 Hydrological process simulations

The calibrated SIMHYD models yielded mean Kling-Gupta Efficiencies $KGE(Q)$ of 0.63 for daily streamflow and 0.81 for monthly streamflow, which are considered good (Knoben et al., 2019). The evapotranspiration ratios simulated in SIMHYD agree well with the Mezentsev-Budyko curve (Figure 2a). All three estimation methods yielded estimates of $\Delta Q_c/\Delta Q$ across the seven stations that are strongly linearly correlated to each other (Figure 2b). The $\Delta Q_c/\Delta Q$ estimated by the elasticity method is very similar to that estimated with SIMHYD (best fit gradient = 1.09, R^2 = 0.98, p<0.001). The hydrological process simulations with SIMHYD consider changes in groundwater and soil moisture storage, which the elasticity method omits. Nevertheless, they had good agreement because the total change in terrestrial water storage (groundwater and soil moisture) was small; on average 0.53% and 0.03% of the total precipitation at all stations in the pre-dam and post-dam naturalized simulations respectively (Figure 2c).

In contrast, the DMC method estimated streamflow to be much less sensitive to climate change compared to the elasticity method and SIMHYD, though its estimates were strongly correlated with those of SIMHYD (best fit gradient = 0.30, R^2 = 1.0, p<0.001) (Figure 2b). The relatively low sensitivity of the DMC method to climate change is likely because it considers only ΔP, but assumes identical E/P in the pre-dam and post-dam periods, and ignores climate change effects on E/P. Changes in $\Delta P/P$ were strongly negatively correlated with E_0/P (R^2 = 0.98, p<0.001), E/P calculated with the elasticity method (R^2 = 0.97, p<0.001), and E/P calculated in SIMHYD (R^2 = 0.92, p<0.001). This implies that changes in precipitation were amplified by accompanying opposite changes to the evapotranspiration ratios: E_0/P and E/P both decreased when precipitation increased, and vice-versa (Figure 2d). Although the changes to the water balance fractions between the pre-dam and post-dam naturalized conditions were small (Figure 2c), and although $\Delta(E/P)$ were small (0.02 mean absolute change), it is important to consider that $\Delta P/P$ were also small (0.03 mean absolute change) (Figure 2d). Hence, the total change in streamflow would be substantially underestimated if one of the two integral components $\Delta P/P$ or $\Delta(E/P)$ were ignored. Therefore, even in the water-limited HRB ($0.9 \leq E_0/P \leq 1.6$), where $\Delta(E/P)$ is relatively insensitive to $\Delta(E_0/P)$ (Figure 2a), the DMC method yielded estimates of $\Delta Q_c/\Delta Q$ that did not quantitatively agree with the other two methods, but qualitatively agreed because $\Delta(E/P)$ consistently amplified the effects of ΔP.

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

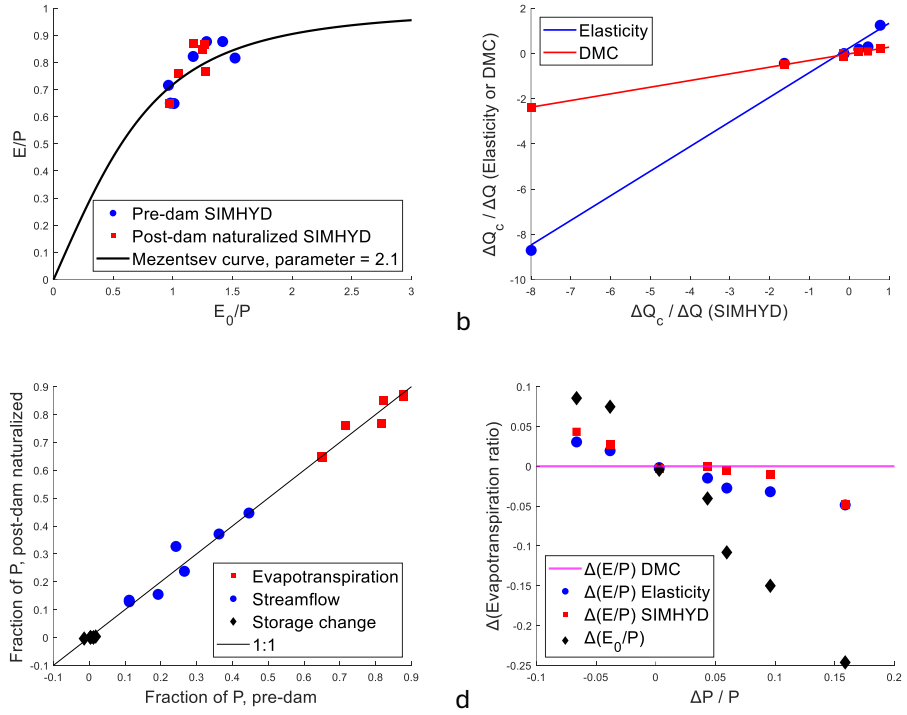


Figure 2: *(a) The actual evapotranspiration ratios and aridity indices at the seven gauge stations simulated in SIMHYD in the pre-dam and post-dam periods, overlain onto the Mezentsev-Budyko curve. (b) The climate change contribution to $\Delta Q/Q$ calculated by the elasticity and DMC methods, against that simulated in SIMHYD. (c) Pre-dam and post-dam naturalized simulations of water balance fractions. (d) Changes in the actual evapotranspiration ratios calculated with the three methods, against the observed changes in aridity indices. Each point represents one of the seven streamflow gauges.*

3.2 Climate change impacts

Between the periods before and after dam construction, climate change increased streamflow by 0.064 to 0.086 mm/d in the Hunter River (station 210015, 210018) (Table 2). In the Rouchel Brook (station 210014), climate change increased streamflow by 0.32 mm/d. Downstream of the Glennies Creek dam, climate change caused large decreases to streamflow, of -0.128 to -0.154 mm/d (station 210044, 210084) (Table 2). In contrast, around the Lostock dam, climate change caused relatively small changes to streamflow, of

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

391 0.034 to 0.064 mm/d (station 210021, 210022). Therefore, the effects of climate change on
392 mean streamflow differed across geographical locations, but were similar within each
393 cluster of geographically close streamflow gauges. These different responses to climate
394 change, although all clusters of streamflow gauges are within a <100 km radius, are likely
395 because of the spatial gradients in elevation, vegetation, and geological conditions in the
396 vicinity of the Hunter River Basin, which intersects the Great Dividing Range of East
397 Australia (Rustomji et al., 2009; Zarate et al., 2025). The average absolute magnitudes of
398 the relative impacts of human activity, on mean streamflow $\langle|F_Q|\rangle$ and streamflow
399 persistence $\langle|F_H|\rangle$, were 0.64 and 0.55 respectively across the seven stations, implying that
400 human activity generally had a greater impact on catchment hydrological processes than
401 climate change within the study area. Furthermore, there are no apparent correlations
402 between F_Q and F_H across individual stations (Table 2), implying that change attribution
403 analyses of F_Q and F_H are complementary and do not provide redundant information.

404

405 Table 2: Decomposition of climate change and human activity impacts on mean streamflow and
406 streamflow persistence between the pre-dam and post-dam observation periods

	Relative impacts of human activity [–]		SIMHYD ΔH_Q [–]		SIMHYD ΔQ [mm/d]		Budyko elasticity ΔQ [mm/d]	Double mass curve ΔQ [mm/d]	Changes to climate parameters [mm/d]	
Station number	F_H	F_Q	Human activity ΔH_{Qh}	Climate change ΔH_{Qc}	Human activity ΔQ_h	Climate change ΔQ_c	Climate change	Climate change	ΔP	ΔE_0
210014	0.48	-0.61	0.040	-0.044	-0.512	0.321	0.086	0.096	0.374	-0.104
210015	0.99	-0.62	0.146	0.002	-0.143	0.086	0.094	0.026	0.236	-0.070
210018	0.69	0.31	0.042	-0.019	0.029	0.064	0.103	0.019	0.161	-0.104
210021	0.42	-0.87	0.020	-0.029	-0.233	0.034	0.007	0.004	0.010	-0.005
210022	0.04	-0.88	0.001	-0.028	-0.500	0.068	0.004	0.069	0.149	0.005
210044	0.39	-0.44	0.013	-0.021	-0.099	-0.128	-0.079	-0.024	-0.113	0.080
210084	0.84	-0.77	0.168	-0.031	-0.510	-0.154	-0.118	-0.063	-0.232	0.056

407

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

3.3 Dam and impounded reservoir effects

3.3.1 Gauges downstream from dams

Gauge station 210021 is near downstream of the Lostock dam, with a human activity induced change of -0.233 mm/d in mean streamflow fluxes (Table 2). Gauge stations 210015 and 210084 are near downstream of dams with large reservoirs (Table 2). The dams altered mean streamflow fluxes by -0.143 mm/d at station 210015, and by -0.510 mm/d at station 210084. The presence of dams and their accompanying reservoirs is known to be able to substantially affect surface and subsurface water levels and fluxes hundreds of kilometers downstream, with effect size depending on the dam and impounded reservoir size, as also shown in this study (Yang et al., 2025; Huang et al., 2023). These effects on downstream hydraulic processes are mediated by discharge control and atmospheric water exchange at the dam (e.g., dam reservoirs enhance evaporation, potentially reducing the total water volume reaching downstream) (Tian et al., 2022), and also by hydraulic pressure propagated through the surface and subsurface water continuum (Shin et al., 2019; Wang et al., 2021). The results show that dam reservoir size alone does not necessarily strongly influence its effects on long-term downstream water balances, because a dam primarily regulates downstream fluxes by changing discharge timings, and secondarily alters water balance terms such as evapotranspiration and subsurface water storage.

The increased H_{Qh} downstream from dams was larger when the dam reservoir was larger (compare stations 210021 ΔH_{Qh} = 0.020, station 210015 ΔH_{Qh} = 0.146, and 210084 ΔH_{Qh} = 0.168). This is because a larger reservoir has a larger water retention capacity, which gives it a larger buffer to continue to release water during prolonged dry periods, and to continue to store water during protracted periods of high flows. Gauge station 210044 is far downstream from the Glennies Creek dam, and the dam's effects on mean streamflow and H_Q here (ΔQ_h = -0.099 mm/d, ΔH_{Qh} = 0.013) are much smaller than at the near downstream station 210084 (ΔQ_h = -0.510 mm/d, ΔH_{Qh} = 0.168) (Table 2). The effects of the dam are attenuated at increased downstream distance because it cannot directly regulate streamflow originating from discharge within the downstream catchment area.

3.3.2 Gauges in unimpaired catchments adjacent to dams

Stations 210014 and 210022 are located in unimpaired streams adjacent to the Glenbawn dam reservoir, and the substantially smaller Lostock dam reservoir, respectively. The

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

simulations show that the dams altered streamflow here by -0.512 mm/d (210014) and -0.497 mm/d (210022), which are larger absolute effect sizes than stations near downstream of dams (Table 2). These are equivalent to -57% of post-dam naturalized streamflow for station 210014 and -31% for station 210022, consistent with the Glenbawn dam having a larger reservoir and hydraulic footprint than the Lostock dam. Although the dams affected mean streamflow notably more than climate change did at these two stations, the dams had similar (210014, ΔH_{Qh} = 0.040, ΔH_{Qc} = -0.044) or smaller (210022, ΔH_{Qh} = 0.001, ΔH_{Qc} = -0.028) effect sizes on H_Q than climate change (Table 2). The small increases in H_Q at non-downstream gauges due to dam effects is consistent with dam effects being mediated by increased evapotranspiration, which has relatively high temporal persistence ($H_E \sim 0.8 > H_Q \sim 0.7 > H_P \sim 0.6$) in the study area.

3.3.3 Gauges upstream from dams

At station 210018 near upstream of the Glenbawn dam, climate change led to increased streamflow of ΔQ_c = 0.064 mm/d, while human activity led to a small positive increase ΔQ_h = 0.029 mm/d, which is the only positive ΔQ_h and thus an outlier amongst all streamflow gauges (Table 2). This result is counterintuitive, given the above analysis of the dam-adjacent streamflow gauges in the unimpaired streams. The presence of the Glenbawn dam should have resulted in increased evapotranspiration at station 210018, caused by increased soil moisture and groundwater levels following subsurface hydraulic interactions with the reservoir. Hence, human activity should have had a negative impact on streamflow at station 210018, similarly to what was observed for stations 210014 and 210022 in adjacent unimpaired streams. However, the Hunter River upstream from station 210018 additionally receives inwards water diversion from other catchments (Figure 1), of up to 20 GL/y (0.072 mm/d) (Dragun et al., 1986), culminating in net slightly positive influence of human activity on the mean streamflow of 0.029 mm/d. This suggests that the Glenbawn dam reduced streamflow at station 210018 by up to 0.043 mm/d, which is a weaker effect than downstream (0.143 mm/d at 210015) or in an adjacent catchment (0.512 mm/d at 210014) (Table 2), possibly because upstream groundwater is deeper due to topography, limiting additional capillary rise and evapotranspiration losses.

Although human activity impacts were mostly masked in the mean streamflow because dam effects and water diversion inputs mostly cancelled out, both the reservoir effects and water diversion inputs would both contribute towards an increase of streamflow persistence and the Hurst exponent, which indeed increased more at station 210018 (ΔH_{Qh}

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

= 0.042) than at any other station except those near-downstream of a large dam (210015, 210084). Thus, the SIMHYD simulations revealed that human activity increased the Hurst exponent and streamflow persistence at station 210018 (Table 2). The increase in upstream evapotranspiration would increase the daily-scale temporal persistence of baseflow and streamflow, because it is associated with decreased temporal variabilities of soil moisture and groundwater levels (Tang et al., 2023; Yan et al., 2024). Additionally, the increased subsurface water retention caused baseflow to become a greater relative contributor to streamflow at the expense of runoff, making the streamflow fluctuate less over time, because baseflow fluctuates less than runoff. Indeed, according to the simulations, the baseflow component of streamflow increased 25% in the post-dam period. Furthermore, the water diversion inputs upstream of station 210018 are also intentionally implemented to supplement periods of low flows and to make streamflow more stable (NSW Government, 2006).

4. Discussion

4.1 Interpreting shifts in hydrological regimes

Summing $\Delta Q_{c,sim}$ and $\Delta Q_{h,sim}$ simulated with SIMHYD yields excellent agreement with the total observed ΔQ (R^2 = 0.98, p<0.001) (Figure 3a). Adding the simulated $\Delta H_{Qc,sim}$ and $\Delta H_{Qh,sim}$ also yields excellent agreement with ΔH_Q of observed streamflow data (R^2 = 0.96, p<0.001) (Figure 3a). These findings reaffirm the accuracy of the calibrated SIMHYD models. Furthermore, this also reveals that $\Delta H_Q \sim \Delta H_{Qc} + \Delta H_{Qh}$ is approximately additive, at least in this case study, unlike most other metrics related to aspects of streamflow variability. Although statistical variances are also additive if each component is assumed to be an independent random variable, the variance is alone not informative about the temporal patterns, persistence, and autocorrelations of streamflow. Furthermore, within a hydroclimatic region, the streamflow mean is weakly correlated to the Hurst exponent (Szolgayova et al., 2012; Markonis et al., 2018) but strongly correlated to the variance (Gottschalk et al., 2026; Betterle et al., 2018), making the streamflow variance a partially redundant indicator of hydrologic regime when paired with the mean. The generality of the first-order additivity of the Hurst exponent in hydrologic change attribution studies could be investigated further in future studies.

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

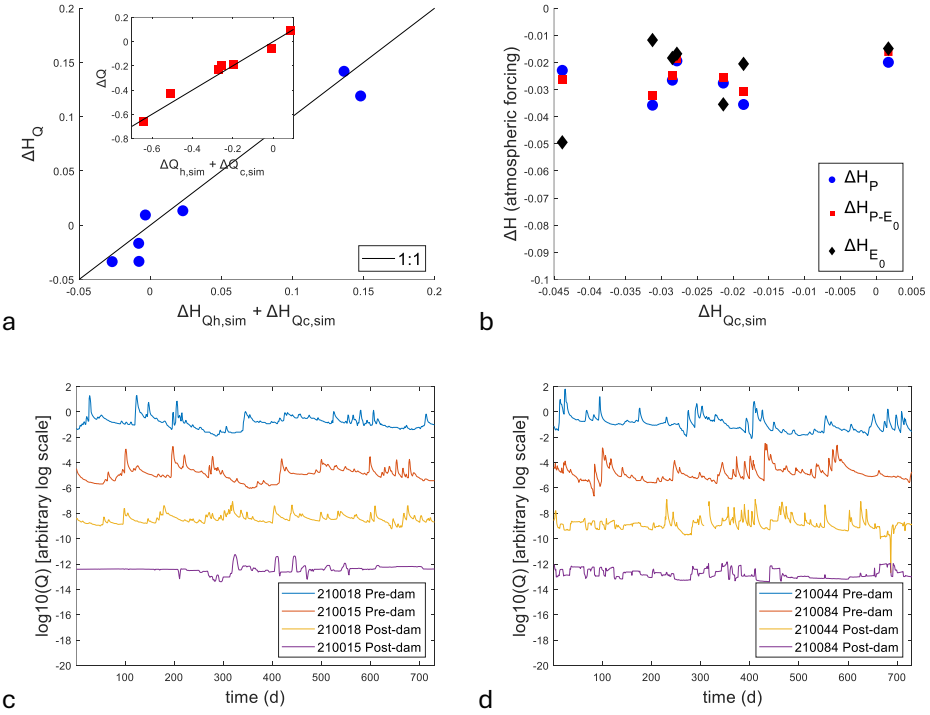


Figure 3: *(a) Observed changes in streamflow Hurst exponent (and mean streamflow in the inset) against the respective changes simulated in SIMHYD. Each point represents one of the seven streamflow gauges. (b) Observed changes in streamflow Hurst exponent against the Hurst exponents of various atmospheric forcing terms. (c) Plot of two years of observed streamflow data at station 210015 (near downstream of a large dam) and station 210018 (near upstream of a large dam) in the pre-dam and post-dam periods, on an arbitrary logarithmic scale. (d) Plot of two years of observed streamflow data at station 210044 (far downstream of a large dam) and station 210084 (near downstream of a large dam) in the pre-dam and post-dam periods, on an arbitrary logarithmic scale.*

The ΔH_{Qc} appears uncorrelated to the changes in the Hurst exponents of atmospheric forcing parameters P, E_0, and $P - E_0$ (Figure 3b). This implies that streamflow persistence is more strongly controlled by catchment hydraulic characteristics than by atmospheric forcing persistence. Note that ΔH_Q at all stations were close to zero (except for 210015 and 210084 immediately downstream of large dams), because ΔH_{Qc} was negative while ΔH_{Qh} was positive (Table 2), underscoring that change attribution analyses focusing on streamflow persistence can reveal important underlying hidden drivers and mechanisms.

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

At stations 210018 ($H_Q = 0.73$) and 210015 ($H_Q = 0.71$), which are upstream and downstream of the Glenbawn dam respectively, in the pre-dam period it is evident that the streamflow timeseries is highly variable with time but preserves some degree of long-term persistence and memory of past states (Figure 3c). In the pre-dam period, these two stations had very similar responses to rainfall and very similar overall streamflow timeseries. Climate change affected H_Q minimally at station 210018 ($\Delta H_{Qc} = -0.019$) and 210015 ($\Delta H_{Qc} = 0.002$) (Table 2). The Glenbawn dam increased streamflow persistence at both stations, but the effect was as expected much greater immediately downstream at station 210015 ($\Delta H_{Qh} = 0.146$) than upstream at station 210018 ($\Delta H_{Qh} = 0.042$). Evidently, the actual post-dam streamflow persistence at station 210018 remained similar to its pre-dam characteristics, whereas streamflow persistence at station 210015 became tightly modulated by the Glenbawn dam (Figure 3c).

The gauge stations near the Glennies Creek dam experienced post-dam decreases in streamflow persistence due to climate change (Table 2). At station 210084 near downstream of the Glennies Creek dam, $\Delta H_{Qc} = -0.031$ and $\Delta H_{Qh} = 0.168$. However, at station 210044 far downstream, $\Delta H_{Qc} = -0.021$ and $\Delta H_{Qh} = 0.013$, which is a similar climate change effect as station 210084 but a much smaller human activity impact. Therefore, these two stations had streamflow persistences that were similar in the pre-dam period, but diverged in the post-dam period (Figure 3d). Thus, streamflow persistence at station 210044 was dominated by the hydrology of its catchment, rather than the fluxes passing through station 210084. Although post-dam extreme low flow occurrences were similarly reduced at these two downstream stations, high flows were strongly attenuated near downstream but not far downstream (Figure 3d), because dams can supplement low flows far downstream but cannot control high flows originating from rainfall in the downstream catchment area. These findings show that hydrologic change attribution methods that integrate streamflow variability together with the classical streamflow mean, enables disentangling the contributions of climate change and human activities to hydrologic shifts, that may not be readily visible from the mean streamflow alone.

4.2 Limitations and implications

Despite the clear physical meaning of the Hurst phenomenon and long-term persistence, the interpretation of a change in the Hurst exponent is not completely straightforward. For example, an increase in H from 0.6 to 0.7, would have different implications for water

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

management than an increase from 0.8 to 0.9. Despite the same difference of 0.1, the former might imply a substantial increase of streamflow persistence that could greatly reduce the short-term risks of unforeseen extreme hydrological events, whereas the latter may not have such significant environmental implications as stable flows becoming even more stable do not necessarily warrant a substantial change in water management strategy. Conversely, the increase from 0.8 to 0.9 increases the likelihood that an extreme event, if it occurs, would last longer, and necessitates a different adaptation in water management strategy. Therefore, the meaning and practical implications of a change to H depends on what the starting point is. Challenges in interpretating changes to the long-term persistence of hydrological processes may thus be a promising avenue for future research. Despite these challenges, before-after comparisons such as those illustrated in this study are relatively straightforward to interpret. This is because the impacts of climate change and human activity on streamflow persistence and the Hurst exponent are imposed upon the same 'before' starting point. Such before-after comparisons constitute the majority of hydrologic change attribution studies, as they yield specific insight for water management in the region (e.g., Terrier et al., 2021; Gao et al., 2017; Luan et al., 2021).

Furthermore, such challenges related to starting point dependence are not unique to the Hurst exponent. Even for the simplest metric of streamflow characteristics, the mean streamflow, an increase from 0.1 mm/d to 0.2 mm/d would have significantly different environmental implications compared to an increase from 2.1 mm/d to 2.2 mm/d, despite an identical 0.1 mm/d difference. Therefore, we do not claim that the Hurst exponent outperforms all other alternatives as a metric related to streamflow variability, but we do show that it is sufficiently simple and interpretable. Moreover, another key utility of the Hurst exponent as a metric is that it is a singular quantity that is informative on streamflow variability from a theoretical and practical water management perspective. By using a singular metric, the separate effects of multiple factors such as climate change and various human activities can be directly compared. This ameliorates the problem of quantitatively incompatible comparisons encountered with existing streamflow variability change attribution methods that use multiple metrics (frequency, duration, etc) concurrently. Furthermore, although the Hurst exponent was applied to determine long-term persistence in the temporal trends of streamflow in this study, it can also be used to determine long-range persistence in spatial trends (O'Connell et al., 2022; O'Connell et al., 2023). Therefore, it is an informative metric for both temporal and spatial streamflow variability, and future research may develop new analyses that integrate spatio-temporal variability together for a unified spatio-temporal characterization of how various driving factors influence hydrological regimes.

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

Another limitation is that the Hurst exponent requires high-resolution streamflow timeseries data of sufficiently long duration to estimate. Existing studies using the Hurst phenomenon to characterize streamflow variability have focused on multi-year records with daily data resolution, or multi-decadal records with monthly data resolution, and the data resolution is mostly at least a hundred times finer than the record length or hydrological time scale of interest (Markonis et al., 2018; Legates & Outcalt, 2022). Therefore, the use of the Hurst exponent for streamflow change attribution is likely not very feasible in ungauged or otherwise data-poor catchments. Nevertheless, this problem is common to all statistical metrics of timeseries variability, and Hurst analysis is not especially hindered by it (Legates & Outcalt, 2022). Moreover, the effects of climate change materialize over decades, and most regions of the world now have access to daily resolution streamflow data for important catchments stretching over at least multiple years if not decades, particularly catchments with significant hydraulic infrastructure. Hence, daily streamflow records spanning at least multiple years is widely available, and higher temporal resolution data, which is less commonly available, may not be necessary.

Despite the above limitations, the attribution of shifts in streamflow variabilities to various potential causes remains an emerging subject in general. A key impediment is that change attribution analyses for streamflow variability is notably more complex than for the mean streamflow. Multiple indicators of flow variability (e.g.: expected X-percentile flows, standard deviation, return period) are typically combined to describe flow variability (Gudmundsson et al., 2025; Magilligan & Nislow, 2005). The 'assessment of hydrologic alteration framework' introduced by Richter et al (1996) is widely used to describe shifts in streamflow variability, but requires calibrating 33 parameters. Thus, the decomposition of hydrologic shifts across multiple causative factors becomes cumbersome, as each parameter would have a different partitioning between each possible causative factor, compounded in complexity by spatial heterogeneity (Cui et al., 2020). Alternatively, attributing changes to the characteristics of discrete hydrological events requires fewer parameters (Yan et al., 2024), but this merely transfers the complexity of the problem to the task of subjective event identification (Khoie et al., 2025). Even then, the issue of multiple indicators of flow variability that are not directly comparable still remains: for instance, Wang et al (2025) found that climate change decreased the frequency of discrete drought events, but human activities increased the duration of such drought events in the Yellow River Basin. Although frequency and duration are physically intuitive concepts, they are not directly comparable in a quantitative sense because flood occurrence is not perfectly

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

periodic. For brevity, this study has addressed the effects of dams on streamflow variability in non-downstream locations using the Hurst exponent as a single information-dense indicator of streamflow variability. Future research may extend the hydrologic change attribution of hydraulic infrastructure to non-downstream locations using a wider array of variability indicators.

4.3 Delineation and separation of climate change and human activity

Many studies have addressed how an observed change in hydrological regimes across the past decades may be separately attributable to changes in climate and non-climate driving forces (Gudmundsson et al., 2025; Terrier et al., 2021). The terminology used in the related literature mostly refers to the separation of the impacts of climate change and human activity on changes to mean streamflows (e.g., Zheng et al., 2026; Gao et al., 2025; Liu et al., 2025). Nevertheless, dams and reservoirs may also alter the local microclimate (Wang et al., 2026; Zhou & Yu, 2025), which is a climate factor that is not necessarily related to global climate change. Conversely, global climate change may influence the terrestrial plant ecology and terrestrial hydrological storage and fluxes, which may be confounded with land-use change or other human activity (Li et al., 2025; Wu et al., 2025), or even directly affect land-use choices (You et al., 2025). Some drivers of hydrologic change fall under neither climate change nor human activity, such as beaver dams (Puttock et al., 2021) and river morphodynamics (Church & Ferguson, 2015). Therefore, boundaries of what counts as the effects of climate change and human activity may be perceived as subjective, and should ideally be precisely defined (Terrier et al.,2021), though this is typically not explicitly addressed in the literature on hydrological change attribution.

In this study, the contribution of climate factors to both metrics of streamflow change specifically refers to the streamflow change that would occur, if the mathematical relationship between precipitation and actual evapotranspiration did not change. This aligns with most hydrologic change attribution literature, and the contribution of human activity then refers collectively to all other factors that do not fall under the category of climate change (Terrier et al., 2021). This study has shown that this definition can be consistently used for the change attribution of mean streamflow, and streamflow persistence. In this study, the precipitation-evapotranspiration mathematical relationships analyzed are: (1) a Budyko-type analytical function that relates evapotranspiration to aridity for the elasticity method, (2) a constant proportionality relation between cumulative precipitation and cumulative evapotranspiration (or streamflow) for the double mass curve

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

method, and (3) hydrological process models in SIMHYD. These three methods yielded consistent estimates of climate change contributions to mean streamflow shifts in the study area, which further affirm the validity of the calibrated SIMHYD models, which were in turn used for the change attribution of streamflow persistence shifts. Hence, although classical widely-used methods of hydrologic change attribution such as the elasticity and double mass curve methods cannot model short-term streamflow changes and cannot directly be used for change attribution analysis of streamflow variability, this study has shown that they can support methods that do have this capability, such as the modeling framework introduced in this study.

4.4 Non-downstream hydrological impacts of dams and reservoirs

This study illustrates that dams can have substantial influence on hydrological processes upstream and in unregulated adjacent catchments, mediated by subsurface hydraulic interactions through groundwater and soil moisture, even though such impacts may not have been intended during the design and construction of the hydraulic infrastructure. Such non-downstream hydrological effects of hydraulic infrastructure can cascade into ecological shifts in biogeochemical processes, and the ecological state of flora and fauna in the unregulated areas (e.g., Pringle, 1997; Sun et al., 2014; Wang et al., 2018; Luo et al., 2021). For example, higher soil moisture caused by raised water tables may enable increased growth or dominance of vegetation adapted to wet soils, while stronger temporal persistence in hydrological conditions may allow for drought-sensitive vegetation to be established (Ridolfi et al., 2000; Tang et al., 2024b; Ozdemir et al., 2026). Compared to downstream effects, the range of non-downstream effects of hydraulic infrastructure may be limited as they are mediated by subsurface hydraulic interactions, which are subject to radially dissipating hydraulic gradients. Nevertheless, this study shows that the non-downstream effects are substantial within a range of 10 km, which can translate into a substantial affected area on the order of 100 km^2. Moreover, the reach of perturbed ecological and biogeochemical conditions may extend beyond the range of the non-downstream dam-induced hydrological changes, for example due to alterations in nutrient and sediment flows, and spatial reorganization of various organisms of different trophic levels (Pringle, 1997; Maavara et al., 2020). Furthermore, non-downstream effects can feedback into, and potentially amplify, downstream effects such as by impeding downstream nutrient fluxes and upstream migration of fish (Greathouse et al., 2006; Maavara et al., 2020). Therefore, relatively short-range hydrological perturbations may affect the resilience of large scale ecological systems (Dekker et al., 2007; Eppinga et al.,

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

2009). Hence, dam and reservoir planning should incorporate nature-positive design considerations that identify and mitigate potential adverse non-downstream impacts.

5 Conclusion

In the Hunter River Basin, streamflow persistence near downstream of two large dams increased substantially in the post-dam period, as expected. However, observed net changes to streamflow persistence were near-zero at other locations, because decreased persistence under climate change were concealed by the persistence-increasing effects of dams, which also propagated upstream and into adjacent catchments. The results also revealed that dam effects on adjacent unimpaired catchments were stronger for streamflow means than for streamflow persistence. Moreover, dam effects on mean streamflow and streamflow persistence in nearby stations upstream and in adjacent catchments, were of comparable or sometimes greater magnitude than the effects on downstream regulated reaches. The impacts of human activity on streamflow averages and streamflow persistence relative to climate change were uncorrelated and different across stations, both in terms of magnitude and sign. These findings highlight the complementarity scientific value of integrating indicators of streamflow variability into hydraulic change attribution analyses. By additionally incorporating change-point detection into the workflow, the methods introduced in this study can be extended to scenarios where the dominant hydrological effects of human activity are gradual and less temporally discrete, such as under reforestation, agricultural expansion, urbanization, and other long-term developments in land-use. Overall, this study has shown that dams and their impounded reservoirs can have large effects on hydrological fluxes and persistence upstream and in adjacent unimpaired catchments, with magnitudes that may be comparable or larger than the effects on downstream locations. To achieve hydraulic infrastructure with nature-positive ecological footprints, non-downstream effects should therefore be a factor in their design and operation.

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

Code and data availability

All data used in this study are available at https://doi.org/10.5281/zenodo.19428694.

Author contributions

Darrell Tang: Conceptualization, Methodology, Funding acquisition, Writing – original draft. **Xiaoyan Song**: Conceptualization, Data Curation, Funding acquisition, Writing – review and editing. **Bjørn Kløve**: Funding acquisition, Writing – review and editing.

Competing interests

The authors declare that they have no conflict of interest.

Financial support

This study was supported by the National Natural Science Foundation of China (W2533117), a Marie Curie European Fellowship (grant number 101205010) under the Horizon Europe programme, and the Digital Waters Flagship funded by the Research Council of Finland (359228).

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

References

Álamos, N., Alvarez-Garreton, C., Muñoz, A., and González-Reyes, Á. The influence of human activities on streamflow reductions during the megadrought in central Chile. Hydrol. Earth Syst. Sci., 28, 2843–2503, https://doi.org/10.5194/hess-28-2483-2024, 2023.

Araya, D., Mendoza, P. A., Muñoz-Castro, E., and McPhee, J. Towards robust seasonal streamflow forecasts in mountainous catchments: impact of calibration metric selection in hydrological modeling. Hydrol. Earth Syst. Sci., 27, 4385–4408, https://doi.org/10.5194/hess-27-4385-2023, 2023.

Betterle, A., Schirmer, M., and Botter, G. Flow dynamics at the continental scale: streamflow correlation and hydrological similarity. Hydrol. Process., 33(4), 627–646, https://doi.org/10.1002/hyp.13350, 2019.

Brunner, M. I., Slater, L., Tallaksen, L. M., and Clark, M. Challenges in modeling and predicting floods and droughts: a review. WIREs Water, 8(3), e1520, https://doi.org/10.1002/wat2.1520, 2021.

Cai, Y., Zhang, J., and Duan, L. Quantitative assessment of the impact of vegetation on riverine nitrogen export: a case study of a boreal forest watershed in the permafrost region of Northeast China. Ecohydrology, 18(8), e70151, https://doi.org/10.1002/eco.70151, 2025.

Chang, C. M. and Yeh, H. D. Spectral analysis of temporal non-stationary rainfall–runoff processes. J. Hydrol., 559, 84–88, https://doi.org/10.1016/j.jhydrol.2018.02.017, 2018.

Chiew, F. H., Peel, M. C., and Western, A. W. Application and testing of the simple rainfall–runoff model SIMHYD. In: Mathematical Models of Small Watershed Hydrology and Applications, edited by: Singh, V. P. and Frevert, D. K., Water Resources Publications, Littleton, CO, USA, 335–367, 2002.

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

786 Church, M. and Ferguson, R. I. Morphodynamics: rivers beyond steady state. Water Resour.
787 Res., 51(4), 1883–1897, https://doi.org/10.1002/2014WR016862, 2015.

788

789 Cui, T., Tian, F., Yang, T., Wen, J., and Khan, M. Y. A. Development of a comprehensive
790 framework for assessing the impacts of climate change and dam construction on flow
791 regimes. J. Hydrol., 590, 125358, https://doi.org/10.1016/j.jhydrol.2020.125358, 2020.

792

793 Dekker, S. C., Rietkerk, M. A. X., and Bierkens, M. F. P. Coupling microscale vegetation–soil
794 water and macroscale vegetation–precipitation feedbacks in semiarid ecosystems. Glob.
795 Change Biol., 13(3), 671–678, https://doi.org/10.1111/j.1365-2486.2007.01327.x, 2007.

796

797 Dey, P. and Mishra, A. Separating the impacts of climate change and human activities on
798 streamflow: a review of methodologies and critical assumptions. J. Hydrol., 548, 278–290,
799 https://doi.org/10.1016/j.jhydrol.2017.03.014, 2017.

800

801 Dragun, A. K., Gleeson, V., and Musgrave, W. F. The Economics of Water Use in the Hunter
802 Region. Centre for Resource and Environmental Studies, Australian National University,
803 Canberra, Australia, 1986.

804

805 Eppinga, M. B., Rietkerk, M., Wassen, M. J., and De Ruiter, P. C. Linking habitat modification
806 to catastrophic shifts and vegetation patterns in bogs. Plant Ecol., 200(1), 53–68,
807 https://doi.org/10.1007/s11258-007-9309-6, 2009.

808

809 Gaál, L., Szolgay, J., Kohnová, S., Parajka, J., Merz, R., Viglione, A., and Blöschl, G. Flood
810 timescales: understanding the interplay of climate and catchment processes through
811 comparative hydrology. Water Resour. Res., 48(4), W04511,
812 https://doi.org/10.1029/2011WR011509, 2012.

813

814 Gao, J., Li, C., Zhou, X., Yi, Y., Wang, X., and Liu, Q. Climate change and human activities
815 amplify runoff variability risks in lower reaches of large rivers. Commun. Earth Environ.,
816 6(1), 794, https://doi.org/10.1038/s43247-025-02759-3, 2025.

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.



817

818 Gao, P., Li, P., Zhao, B., Xu, R., Zhao, G., Sun, W., and Mu, X. Use of double mass curves in
819 hydrologic benefit evaluations. Hydrol. Process., 31(26), 4639–4646,
820 https://doi.org/10.1002/hyp.11377, 2017.

821

822 Gottschalk, L., Krasovskaia, I., Leblois, E., and Sauquet, E. Mapping mean and variance of
823 runoff in a river basin. Hydrol. Earth Syst. Sci., 10(4), 469–484,
824 https://doi.org/10.5194/hess-10-469-2006, 2006.

825

826 Greathouse, E. A., Pringle, C. M., McDowell, W. H., and Holmquist, J. G. Indirect upstream
827 effects of dams: consequences of migratory consumer extirpation in Puerto Rico. Ecol.
828 Appl., 16(1), 339–352, https://doi.org/10.1890/05-0243, 2006.

829

830 Gudmundsson, L., Brunner, M. I., Döll, P., Fluet-Chouinard, E., Frolova, N., Gosling, S. N.,
831 Hattermann, F., Larrey-Lassalle, P., Masaki, Y., Müller Schmied, H., Sayre, N. F., Stacke, T.,
832 and Zhou, X. Past and future change in global river flows. Nat. Rev. Earth Environ., 7, 7–23,
833 https://doi.org/10.1038/s43017-025-00745-z, 2025.

834

835 Hansford, M. R., Plink-Björklund, P., and Jones, E. R. Global quantitative analyses of river
836 discharge variability and hydrograph shape with respect to climate types. Earth-Sci. Rev.,
837 200, 102977, https://doi.org/10.1016/j.earscirev.2019.102977, 2020.

838

839 Hao, H., Dong, N., Yang, M., Wei, J., Zhang, X., Xu, S., ... & Kunstmann, H. The changing
840 hydrology of an irrigated and dammed Yangtze River: streamflow, extremes, and lake
841 hydrodynamics. Water Resour. Res., 60(10), e2024WR037841,
842 https://doi.org/10.1029/2024WR037841, 2024.

843

844 Huang, P., Zhou, A., Ma, C., Guo, J., Wang, Y., Fan, W., and Li, W. Impact of the Three Gorges
845 Dam on the spatial and temporal variation of groundwater level in Jianghan Plain using STL
846 algorithm. Environ. Earth Sci., 82, 417, https://doi.org/10.1007/s12665-023-11110-y, 2023.

847

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

Hurst, H. E. Long-term storage capacity of reservoirs. Trans. Am. Soc. Civ. Eng., 116(1), 770–799, 1951. https://doi.org/10.1061/TACEAT.0006518, 1951.

Kåresdotter, E., Destouni, G., Ghajarnia, N., Lammers, R. B., and Kalantari, Z. Distinguishing direct human-driven effects on the global terrestrial water cycle. Earth's Future, 10(8), e2022EF002848, https://doi.org/10.1029/2022EF002848, 2022.

Khoie, M. M. M., Guo, D., and Wasko, C. Improving the consistency of hydrologic event identification. Environ. Model. Softw., 191, 106521, https://doi.org/10.1016/j.envsoft.2025.106521, 2025.

Kirchner, J. W. and Neal, C. Universal fractal scaling in stream chemistry and its implications for solute transport and water quality trend detection. Proc. Natl. Acad. Sci. USA, 110(30), 12213–12218, https://doi.org/10.1073/pnas.1304328110, 2013.

Knoben, W. J. M., Freer, J. E., and Woods, R. A. Inherent benchmark or not? Comparing Nash–Sutcliffe and Kling–Gupta efficiency scores. Hydrol. Earth Syst. Sci., 23, 4323–4331, https://doi.org/10.5194/hess-23-4323-2019, 2019.

Koutsoyiannis, D. Climate change, the Hurst phenomenon, and hydrological statistics. Hydrol. Sci. J., 48(1), 3–24, https://doi.org/10.1623/hysj.48.1.3.43481, 2003.

Le Moine, N., Andréassian, V., Perrin, C., and Michel, C. How can rainfall–runoff models handle intercatchment groundwater flows? Theoretical study based on 1040 French catchments. Water Resour. Res., 43(6), W06428, https://doi.org/10.1029/2006WR005608, 2007.

Legates, D. R. and Outcalt, S. I. Detection of climate transitions and discontinuities by Hurst rescaling. Int. J. Climatol., 42(9), 4753–4772, https://doi.org/10.1002/joc.7502, 2022.

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.



878 Liu, Y., Wang, F., Zhang, S., Wang, H., Li, R., Han, J., ... & Shi, S. Have human activities been
879 accurately evaluated in sediment yield changes in the middle reaches of the Yellow River?
880 J. Environ. Manag., 373, 123860, https://doi.org/10.1016/j.jenvman.2025.123860, 2025.

881

882 Luan, J., Zhang, Y., Ma, N., Tian, J., Li, X., and Liu, D. Evaluating the uncertainty of eight
883 approaches for separating the impacts of climate change and human activities on
884 streamflow. J. Hydrol., 601, 126605, https://doi.org/10.1016/j.jhydrol.2021.126605, 2021.

885

886 Luo, Z., Shao, Q., and Liu, H. Comparative evaluation of river water quality and ecological
887 changes at upstream and downstream sites of dams/sluices in different regulation
888 scenarios. J. Hydrol., 597, 126290, https://doi.org/10.1016/j.jhydrol.2021.126290, 2021.

889

890 Maavara, T., Chen, Q., Van Meter, K., Brown, L. E., Zhang, J., Ni, J., and Zarfl, C. River dam
891 impacts on biogeochemical cycling. Nat. Rev. Earth Environ., 1, 103–116,
892 https://doi.org/10.1038/s43017-019-0019-0, 2020.

893

894 Magilligan, F. J. and Nislow, K. H. Changes in hydrologic regime by dams. Geomorphology,
895 71, 61–78, https://doi.org/10.1016/j.geomorph.2004.08.017, 2005.

896

897 Markonis, Y., Moustakis, Y., Nasika, C., Sychova, P., Dimitriadis, P., Hanel, M., and
898 Papalexiou, S. M. Global estimation of long-term persistence in annual river runoff. Adv.
899 Water Resour., 113, 1–12, https://doi.org/10.1016/j.advwatres.2018.01.003, 2018.

900

901 Meng, Y., Jiang, L., Du, E., Zhang, X., Wang, W., and Wang, L. A new understanding of the
902 Poyang Lake–Yangtze River interaction: a backwater effect on the Yangtze River
903 perspective. Geophys. Res. Lett., 52(7), e2025GL114807,
904 https://doi.org/10.1029/2025GL114807, 2025.

905

906 O'Connell, E., O'Donnell, G., and Koutsoyiannis, D. The spatial scale dependence of the
907 Hurst coefficient in global annual precipitation data, and its role in characterising regional

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.



908 precipitation deficits within a naturally changing climate. Hydrology, 9(11), 199,
909 https://doi.org/10.3390/hydrology9110199, 2022.

910

911 O'Connell, E., O'Donnell, G., and Koutsoyiannis, D. On the spatial scale dependence of
912 long-term persistence in global annual precipitation data and the Hurst phenomenon.
913 Water Resour. Res., 59(4), e2022WR033133, https://doi.org/10.1029/2022WR033133,
914 2023.

915

916 O'Connell, P. E., Koutsoyiannis, D., Lins, H. F., Markonis, Y., Montanari, A., and Cohn, T. The
917 scientific legacy of Harold Edwin Hurst (1880–1978). Hydrol. Sci. J., 61, 1571–1590,
918 https://doi.org/10.1080/02626667.2015.1125998, 2016.

919

920 Ozdemir, B., Bektas, H., and Ulker, M. Deep rooting in bread wheat is more strongly
921 associated with genotypes than drought stress: evidence from Van Lake Basin genotypes.
922 Front. Plant Sci., 17, 1887215, https://doi.org/10.3389/fpls.2026.1887215, 2026.

923

924 Peel, M. C., Chiew, F. H., Western, A. W., and McMahon, T. A. Extension of unimpaired
925 monthly streamflow data and regionalisation of parameter values to estimate streamflow
926 in ungauged catchments. Report to the National Land and Water Resources Audit, Centre
927 for Environmental Applied Hydrology, The University of Melbourne, Melbourne, Australia,
928 2000.

929

930 Pizarro, A., Acuña, P., Dimitriadis, P., Iliopoulou, T., and Koutsoyiannis, D. Past, present, and
931 future of the Hurst–Kolmogorov dynamics in Stochastics: a bibliometric analysis of the last
932 50 years in water resources. J. Hydrol., 643, 132008,
933 https://doi.org/10.1016/j.jhydrol.2024.132008, 2024.

934

935 Pringle, C. M. Exploring how disturbance is transmitted upstream: going against the flow. J.
936 N. Am. Benthol. Soc., 16(2), 425–438, https://doi.org/10.2307/1468028, 1997.

937

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.



938 Puttock, A., Graham, H. A., Ashe, J., Luscombe, D. J., and Brazier, R. E. Beaver dams
939 attenuate flow: a multi-site study. Hydrol. Process., 35(2), e14017,
940 https://doi.org/10.1002/hyp.14017, 2021.

941

942 Quinn, N. W. Adaptive implementation of information technology for real-time, basin-scale
943 salinity management in the San Joaquin Basin, USA and Hunter River Basin, Australia.
944 Agric. Water Manag., 98(6), 930–940, https://doi.org/10.1016/j.agwat.2010.11.013, 2011.

945

946 Rao, A. R. and Bhattacharya, D. Comparison of Hurst exponent estimates in
947 hydrometeorological time series. J. Hydrol. Eng., 4(3), 225–231,
948 https://doi.org/10.1061/(ASCE)1084-0699(1999)4:3(225) , 1999.

949

950 Richter, B. D., Baumgartner, J. V., Powell, J., and Braun, D. P. A method for assessing
951 hydrologic alteration within ecosystems. Conserv. Biol., 10(4), 1163–1174,
952 https://doi.org/10.1046/j.1523-1739.1996.10041163.x, 1996.

953

954 Ridolfi, L., D'Odorico, P., Porporato, A., and Rodriguez-Iturbe, I. Impact of climate variability
955 on the vegetation water stress. J. Geophys. Res. Atmos., 105, 18013–18025,
956 https://doi.org/10.1029/2000JD900206, 2000.

957

958 Rosa, L. and Sangiorgio, M. Global water gaps under future warming levels. Nat. Commun.,
959 16, 1192, https://doi.org/10.1038/s41467-025-56517-2, 2025.

960

961 Rustomji, P., Bennett, N., and Chiew, F. Flood variability east of Australia's Great Dividing
962 Range. J. Hydrol., 374, 196–208, https://doi.org/10.1016/j.jhydrol.2009.06.017, 2009.

963

964 Shen, H., Tolson, B. A., and Mai, J. Time to update the split-sample approach in
965 hydrological model calibration. Water Resour. Res., 58(3), e2021WR031523,
966 https://doi.org/10.1029/2021WR031523, 2022.

967

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

968 Shin, S., Pokhrel, Y., and Miguez-Macho, G. High-resolution modeling of reservoir release
969 and storage dynamics at the continental scale. Water Resour. Res., 55(1), 787–810,
970 https://doi.org/10.1029/2018WR023025, 2019.

971

972 Singh, N. K. and Basu, N. B. The human factor in seasonal streamflows across natural and
973 managed watersheds of North America. Nat. Sustain., 5, 397–405,
974 https://doi.org/10.1038/s41893-022-00848-1, 2022.

975

976 Singh, R., Archfield, S. A., and Wagener, T. Identifying dominant controls on hydrologic
977 parameter transfer from gauged to ungauged catchments: a comparative hydrology
978 approach. J. Hydrol., 517, 985–996, https://doi.org/10.1016/j.jhydrol.2014.06.030, 2014.

979

980 Song, X., Sun, W., Zhang, Y., Song, S., Li, J., and Gao, Y. Using hydrological modelling and
981 data-driven approaches to quantify mining activities impacts on centennial streamflow. J.
982 Hydrol., 585, 124764, https://doi.org/10.1016/j.jhydrol.2020.124764, 2020.

983

984 Spink, A., Fryirs, K., and Brierley, G. The relationship between geomorphic river adjustment
985 and management actions over the last 50 years in the upper Hunter catchment, NSW,
986 Australia. River Res. Appl., 25(7), 904–928, https://doi.org/10.1002/rra.1197, 2009.

987

988 Srikanthan, S., McMahon, T., and Peel, M. Recommended daily rainfall-runoff model for
989 Australian hydrology consulting. Australas. J. Water Resour., 29(2), 163–181,
990 https://doi.org/10.1080/13241583.2025.2547443, 2025.

991

992 Sun, R., Deng, W. Q., Yuan, X. Z., Liu, H., and Zhang, Y. W. Riparian vegetation after dam
993 construction on mountain rivers in China. Ecohydrology, 7(4), 1187–1195,
994 https://doi.org/10.1002/eco.1450, 2014.

995

996 Szolgayova, E., Laaha, G., Blöschl, G., and Bucher, C. Factors influencing long range
997 dependence in streamflow of European rivers. Hydrol. Process., 28(4), 1573–1586,
998 https://doi.org/10.1002/hyp.9694, 2014.

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

Tang, D., French, H. K., Leijnse, A., Bartholomeus, R. P., and van der Zee, S. E. Reactive contaminant infiltration under dynamic preferential flow. J. Hydrol., 634, 131111, https://doi.org/10.1016/j.jhydrol.2024.131111, 2024a.

Tang, D., Bartholomeus, R. P., and Ritsema, C. J. Wastewater irrigation beneath the water table: analytical model of crop contamination risks. Agric. Water Manag., 298, 108848, https://doi.org/10.1016/j.agwat.2024.108848, 2024b.

Tang, D., Van der Zee, S. E., Narain-Ford, D. M., van den Eertwegh, G. A., and Bartholomeus, R. P. Managed phreatic zone recharge for irrigation and wastewater treatment. J. Hydrol., 626, 130208, https://doi.org/10.1016/j.jhydrol.2023.130208, 2023.

Teng, J., Chiew, F. H. S., Vaze, J., Marvanek, S., and Kirono, D. G. C. Estimation of climate change impact on mean annual runoff across continental Australia using Budyko and Fu equations and hydrological models. J. Hydrometeorol., 13(3), 1094–1106, https://doi.org/10.1175/JHM-D-11-097.1, 2012.

Terrier, M., Perrin, C., De Lavenne, A., Andréassian, V., Lerat, J., and Vaze, J. Streamflow naturalization methods: a review. Hydrol. Sci. J., 66(1), 12–36, https://doi.org/10.1080/02626667.2020.1839080, 2021.

Tian, W., Liu, X., Wang, K., Bai, P., Liu, C., and Liang, X. Estimation of global reservoir evaporation losses. J. Hydrol., 607, 127524, https://doi.org/10.1016/j.jhydrol.2022.127524, 2022.

Van Loon, A. F., Rangecroft, S., Coxon, G., Werner, M., Wanders, N., Di Baldassarre, G., ... & Van Lanen, H. A. Streamflow droughts aggravated by human activities despite management. Environ. Res. Lett., 17, 044059, https://doi.org/10.1088/1748-9326/ac5def, 2022.

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

Vogel, R. M., Lall, U., Cai, X., Rajagopalan, B., Weiskel, P. K., Hooper, R. P., and Matalas, N. C. Hydrology: the interdisciplinary science of water. Water Resour. Res., 51(6), 4409–4430, https://doi.org/10.1002/2015WR017049, 2015.

Wang, D. and Hejazi, M. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. Water Resour. Res., 47(10), W00J12, https://doi.org/10.1029/2010WR010283, 2011.

Wang, F., Maberly, S. C., Wang, B., and Liang, X. Effects of dams on riverine biogeochemical cycling and ecology. Inland Waters, 8, 130–140, https://doi.org/10.1080/20442041.2018.1469335, 2018.

Wang, L., Li, Y., Biswas, A., Zhao, Y., Niu, B., and Siddique, K. H. M. Assessing climate change and human impacts on runoff and hydrological droughts in the Yellow River Basin using a machine learning-enhanced hydrological modeling approach. J. Environ. Manag., 380, 125091, https://doi.org/10.1016/j.jenvman.2025.125091, 2025.

Wang, N., Xu, Z., Xu, Y., Yang, Y., Cong, N., and Yao, W. From climate-driven to dam-regulated: impacts of dams on riparian vegetation in a mountainous river system. Catena, 265, 109879, https://doi.org/10.1016/j.catena.2025.109879, 2026.

Wang, S., Pan, Y., Wang, L., Guo, F., Chen, Y., and Sun, W. Deformation characteristics, mechanisms, and influencing factors of hydrodynamic pressure landslides in the Three Gorges Reservoir: a case study and model test study. Bull. Eng. Geol. Environ., 80, 3513–3533, https://doi.org/10.1007/s10064-021-02120-w, 2021.

Xiong, J. and Yang, Y. Climate change and hydrological extremes. Curr. Clim. Change Rep., 11, 1, https://doi.org/10.1007/s40641-024-00198-4, 2024.

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

Yan, X., Nunes, J. P., Sun, J., Tang, D. W., Wen, Y., and Li, Z. Restored vegetation dominates the decrease in surface and subsurface runoff on the Loess Plateau. J. Hydrol., 640, 131730, https://doi.org/10.1016/j.jhydrol.2024.131730, 2024.

Yang, H., Yang, D., Lei, Z., and Sun, F. New analytical derivation of the mean annual water–energy balance equation. Water Resour. Res., 44(3), W03410, https://doi.org/10.1029/2007WR006135, 2008.

Yang, X., Zhang, S., Tang, C., Wu, C., and Ge, Y. Impact of Three Gorges Dam construction on spatiotemporal variations in the hydrodynamic regime of Poyang Lake (China). J. Hydrol., 646, 132302, https://doi.org/10.1016/j.jhydrol.2025.132302, 2025.

Zarate, E., Andersen, M. S., Rau, G. C., Acworth, R. I., Rutlidge, H., MacDonald, A. M., and Cuthbert, M. O. How alluvial storage controls spatiotemporal water balance partitioning in intermittent and ephemeral stream systems. Water Resour. Res., 61(4), e2024WR037256, https://doi.org/10.1029/2024WR037256, 2025.

Zhan, P., Jiang, L., Liu, K., Chen, T., Fan, C., Zeng, F., and Song, C. Unveiling the floodplain river–lake hydrological interactions by SWOT observations. Geophys. Res. Lett., 52(24), e2025GL118459, https://doi.org/10.1029/2025GL118459, 2025.

Zhang, H. Y., Feng, Z. Q., Feng, S. Y., and Zhou, Y. Typical algorithms for estimating Hurst exponent of time sequence: a data analyst's perspective. IEEE Access, 12, 185528–185556, https://doi.org/10.1109/ACCESS.2024.3512542, 2024.

Zhang, Y., Blöschl, G., Wei, H., Kong, D., Ma, N., Wagener, T., ... & Liu, C. Overestimation of past and future increases in global river flow by Earth system models. Nat. Geosci., 19, 311-316. https://doi.org/10.1038/s41561-025-01897-9, 2026.

Zhang, Y. Q., Rachakonda, P. K., Herron, N. F., Peña-Arancibia, J. L., and Marvanek, S. P. Current water accounts and water quality for the Hunter subregion. Product 1.5 for the

https://doi.org/10.5194/egusphere-2026-5096
Preprint. Discussion started: 17 November 2026
© Author(s) 2026. CC BY 4.0 License.

Hunter subregion from the Northern Sydney Basin Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO, and Geoscience Australia, Australia, 2016.

Zheng, W., Wang, S., Sun, H., Shen, Y., and Cao, J. Rainfall-driven nitrate transport in runoff of hilly area by combining time-series monitoring of hydrochemistry and stable isotopes. J. Hydrol., 654, 132830, https://doi.org/10.1016/j.jhydrol.2025.132830, 2025.

Zhou, S., Yu, B., Huang, Y., and Wang, G. The complementary relationship and generation of the Budyko functions. Geophys. Res. Lett., 42(6), 1781–1790, https://doi.org/10.1002/2015GL063511, 2015.

Zhou, S., Yu, B., and Zhang, Y. Global concurrent climate extremes exacerbated by anthropogenic climate change. Sci. Adv., 9, eabo1638, https://doi.org/10.1126/sciadv.abo1638, 2023.

Zhou, S. and Yu, B. Neglecting land–atmosphere feedbacks overestimates climate-driven increases in evapotranspiration. Nat. Clim. Change, 15, 1099–1106, https://doi.org/10.1038/s41558-025-02428-5, 2025.