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Catchments do not strictly follow Budyko curves over multiple decades, but deviations are minor and predictable

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S1 Movement of catchments in Budyko space between subsequent 20-year periods

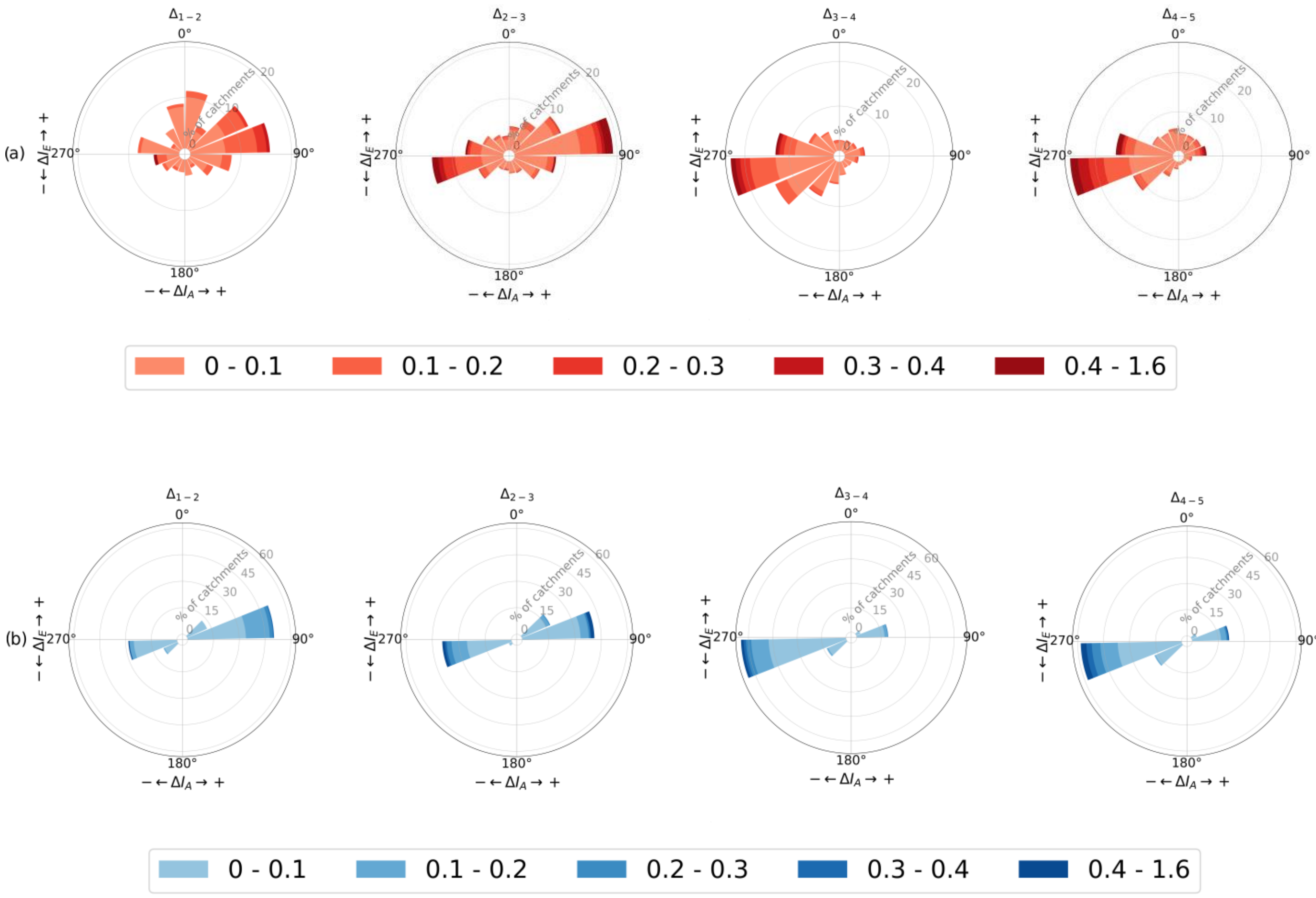

Figure S1: Diagrams depicting the movement of catchments in the Budyko space between two subsequent 20-year periods over a 100-year study period. The colour gradients represent the intensity of movement. Each bar present a direction range of 22.5 degree a) Diagrams illustrating total change b) Diagrams illustrating change attributed solely due to variations in the *I_A*.

The differences in I_A between the individual time periods, represented by movement along the x-axis of the I_A-I_E Budyko space, and differences in I_E, expressed by movement along the y-axis, led to characteristic directions and magnitudes of actual movement of individual catchments in the I_A-I_E Budyko space, inferred from observations of ΔI_A and ΔI_E, between the individual 20-year periods (Jaramillo and Destouni, 2014; Van Der Velde et al., 2014).

The right-ward direction of movement, represented by angles 0 < α < 180° in the I_A-I_E Budyko space, reflects a shift towards overall more arid conditions for the majority of catchments in the early 20th century, which is followed by a clear left-ward movement (180 < α < 360°) towards more humid conditions for the later parts of the century. This pattern of observed movement is contrasted by the expected movement in the I_A-I_E Budyko space, inferred from ΔI_E. The directions of expected movement (Fig. S1b) exhibit comparable pattern with Fig. S1a. Overall, movement towards somewhat more arid conditions between the first time periods (45° < α < 90°) and towards more humid conditions later on (225 < α < 270°) can be seen. If individual catchments, in response to ΔI_A, followed their specific curves defined by ω, the movement directions resulting from observed ΔI_E (Fig. S1a) would not only have to be constrained to the ranges 45° < α < 90° and 225 < α < 270° but they would be equal to those resulting from expected ΔI_E. As a consequence, Fig. S1a and Fig. S1b would have to show identical pattern. By inversion, the difference between the Fig. S1a and Fig. S1b illustrates that not all catchments follow their specific curves and thus suggests the presence of vertical deviations $\varepsilon_{IE\omega} \neq 0$ from expected I_E.

S2 Mean 20-year changes in hydro-climatic variables across studied catchments between subsequent 20-year periods with consistent sample size

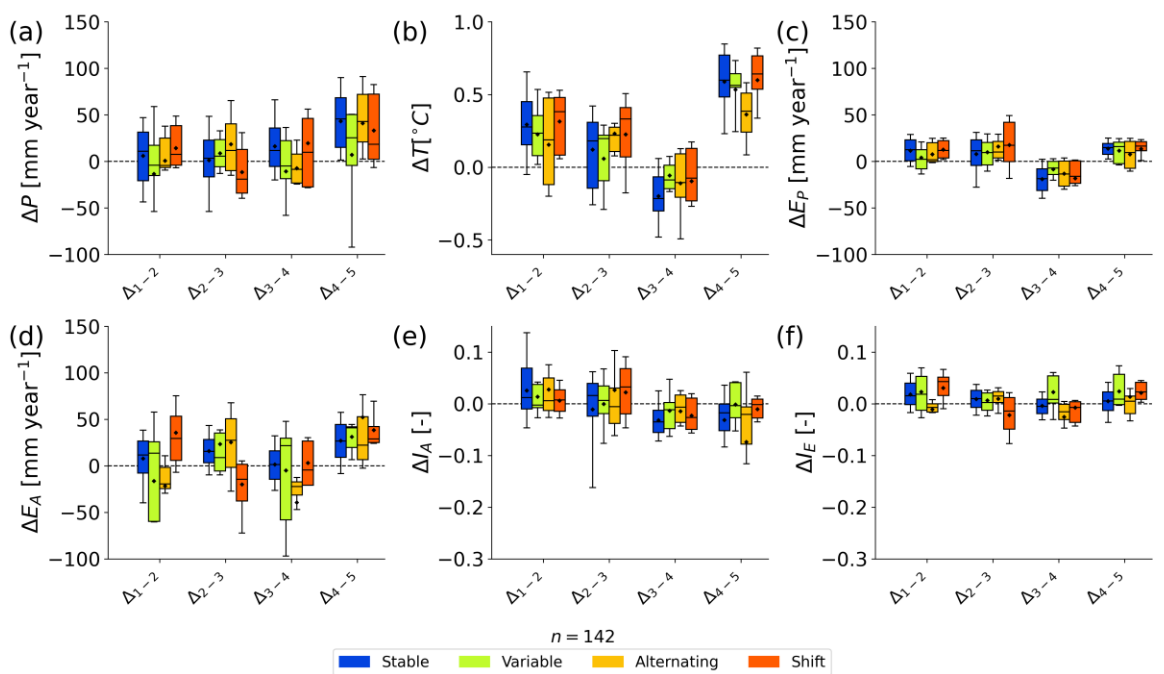

Figure S2: Temporal stability category-wise mean 20-year changes in hydro-climatic variables for the studied catchments between two consecutive periods. a) Precipitation *P*, b) Temperature *T*, c) Potential evaporation E_P, d) Actual evaporation E_A, e) Aridity index I_A, and f) Evaporative index I_E. The boxes represent the 25th to 75th percentiles, while whiskers extend to the 10th and 90th percentiles. Diamonds denote the arithmetic mean, and outliers are not shown.

S3 Potential factors influencing the alternating and shifting behaviour of Kaituna River and Zschopau River

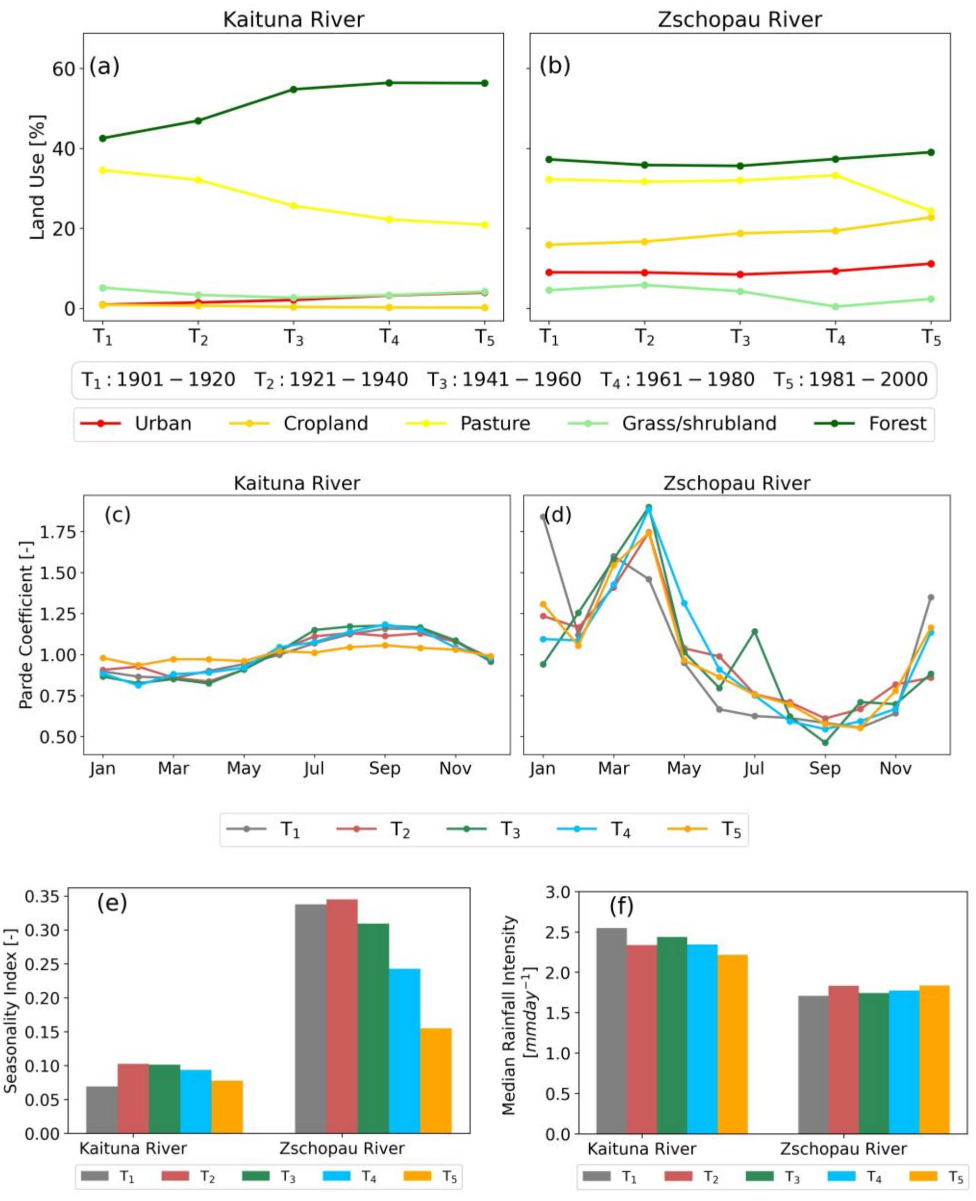

Figure S3: Land use changes (a-b), Parde Coefficients (c-d), Seasonality Index of liquid precipitation input (e), and Median rainfall intensity (f) for two example catchments (Kaituna and Zschopau) across five 20-year periods (T_1–T_5).

S4 Dependency between $I_{E,i}$ and median $\varepsilon_{IE\omega}$ for Sava and Kaituna River catchments

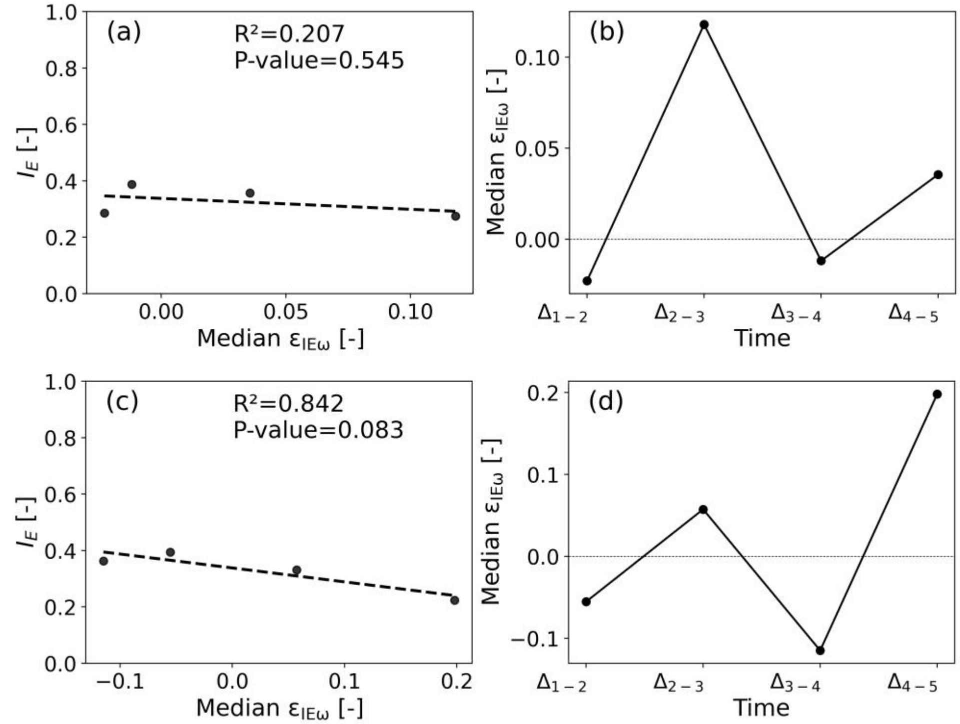

Figure S4: a) Correlation between I_E and median $\varepsilon_{IE\omega}$ (a and c) and temporal evolution of median $\varepsilon_{IE\omega}$ (b and d) for the Save River (top) and Kaituna River (bottom) catchments, respectively.

S5 Three additional examples of well-known river basins

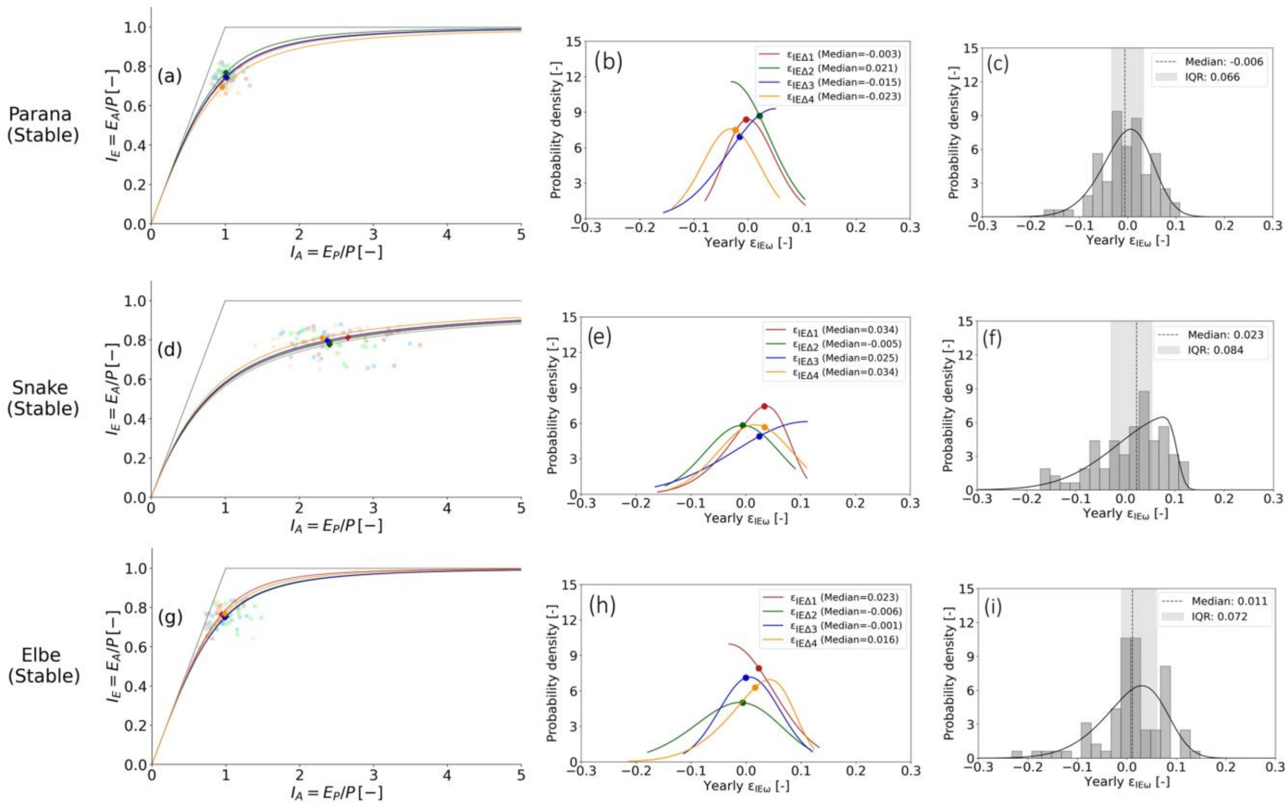

Figure S5: Mean annual position of catchments (light colour dots) in Budyko space along with long-term mean (dark colour dots) and predictive parametric Budyko curves (left column). Individual distribution of deviations ($\varepsilon_{IE\Delta1}$, $\varepsilon_{IE\Delta2}$, $\varepsilon_{IE\Delta3}$ and $\varepsilon_{IE\Delta4}$) with long term median deviation $\epsilon_{IE\omega}$ values (middle column) and long-term marginal distribution of annual deviations along with long-term median values of $\varepsilon_{IE\omega}$ and IQR of $\varepsilon_{IE\omega}$ values (right column) for three example catchment: Parana River (a-c), Snake River (d-f), Elbe River (g-i).

In the case of Parana River basin (Argentina; 891832 km^2; ID AR_0000001), tagged as "Stable" on basis of all four 20-year distributions ("o o o o"), the marginal distribution has a median deviation $\varepsilon_{IE\omega}$ ~ -0.006 with a narrow IQR ~ 0.066 (Fig. S5c). Similarly, the Snake River (Fig. S5d-f), the largest tributary to the Columbia river system (US; 156061 km^2; ID US_0008712), was also tagged as "Stable", in spite of some more pronounced fluctuations over the four periods with a median $\varepsilon_{IE\omega}$ ~ 0.023 but a slightly higher IQR ~ 0.084 (Fig. S5f). The Elbe River (Germany; 90277 km^2; ID DE_0000724) exhibits somehow similar distributions of $\varepsilon_{IE\omega}$. The four median deviations varies between -0.006 to 0.023 (Fig. S5h) and the annual spread remains very low IQR ~ 0.072 (Fig. S5i). As a consequence this river basin was tagged as "Stable", too.

S6 Catchment median $\varepsilon_{IE\omega}$ and temporal stability analysis with fixed baseline approach

Whether a fixed baseline can provide additional insights, we conducted the analysis in which we fixed the oldest available 20-year period as the baseline and calculated distributions of deviations for the subsequent 20-year periods accordingly and are illustrated in Fig. S6a-f. For the first example catchment (Chemung River, Fig. 6b-c in the manuscript), we observed that the results from both approaches were almost identical (Fig. S6a-b). However, for the second example catchment (Lee River, Fig. 6e-f in the manuscript), the median deviations were somewhat higher when using a fixed baseline (Fig. S6c-d).

We also extended this analysis to all other study catchments. However, please note that we could include the full 100-year period in only 159 out of 2387 catchments. For the other catchments, we used the oldest available 20-year period as the fixed baseline. We have found that the proportion of "Stable" catchments increased from 72 % (temporally changing-dynamic baseline) to 84 % (fixed baseline) (Fig. S6f), suggesting that temporally changing baselines are more sensitive to capturing recent shifts and trends in hydrological behaviour, which helps to assign catchments to one of the four categories. In contrast, while the number of “Stable” catchments increased, we also observed that the median $\varepsilon_{IE\omega}$ of the aggregated marginal distributions of $\varepsilon_{IE\omega}$ were slightly higher when using a fixed baseline (Fig. S6e).

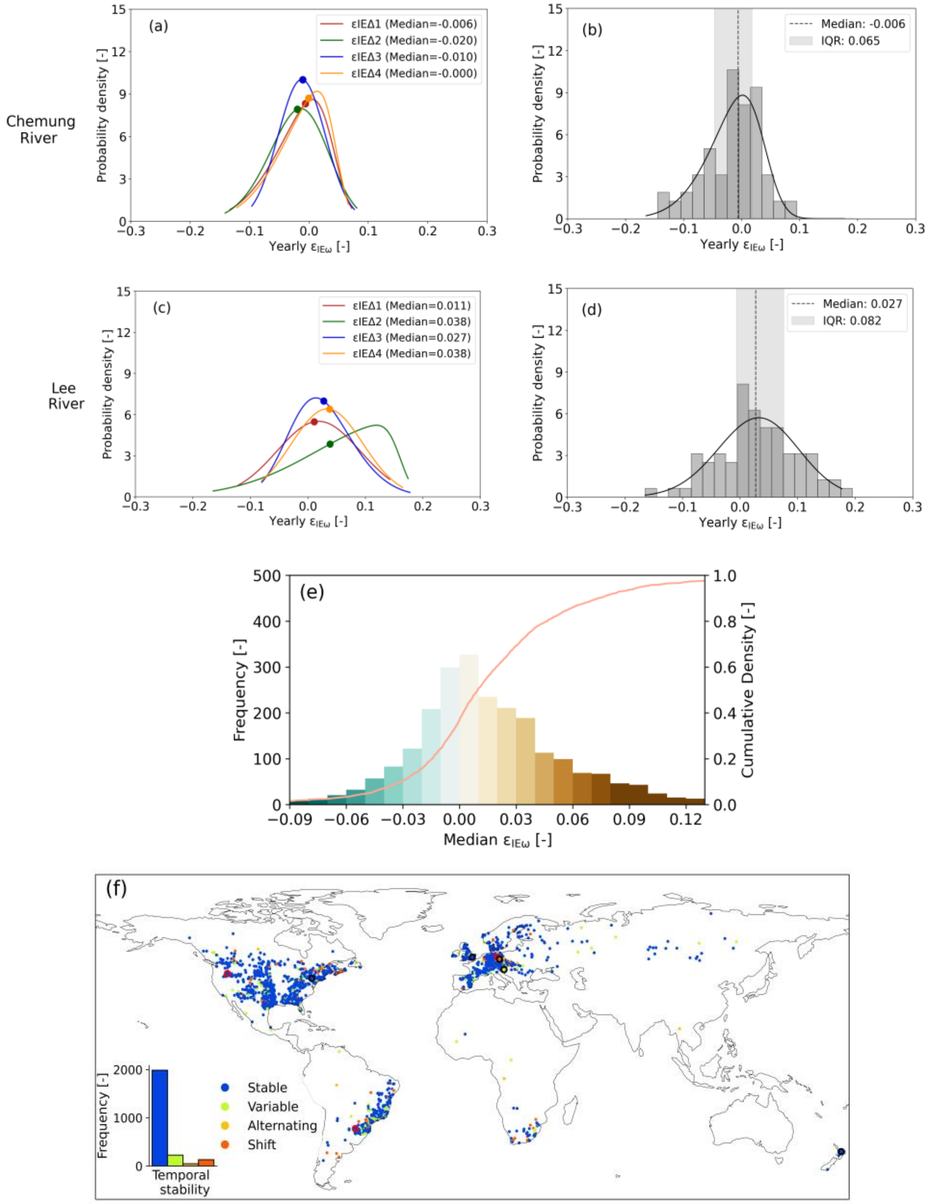

Figure S6: Individual distribution of deviations ($\varepsilon_{IE\Delta1}$, $\varepsilon_{IE\Delta2}$, $\varepsilon_{IE\Delta3}$ and $\varepsilon_{IE\Delta4}$) along with the long-term marginal distribution of annual deviations for the Chemung River (a-b) and Lee River (c-d). Panel (e) shows the long-term median $\epsilon_{IE\omega}$ values of aggregated marginal distribution of $\epsilon_{IE\omega}$ across all catchments (2387), while panel (f) illustrates the temporal stability of the studied catchments using fixed base line approach. Catchments highlighted with a black border represent the 5 selected examples from Fig. 6 in the manuscript, while those outlined in red denote three additional selected example catchments shown in Fig. S5.

S7 Comparative analysis of median $\varepsilon_{IE\omega}$ with respect to topographic characteristics and climatic indices of study catchments

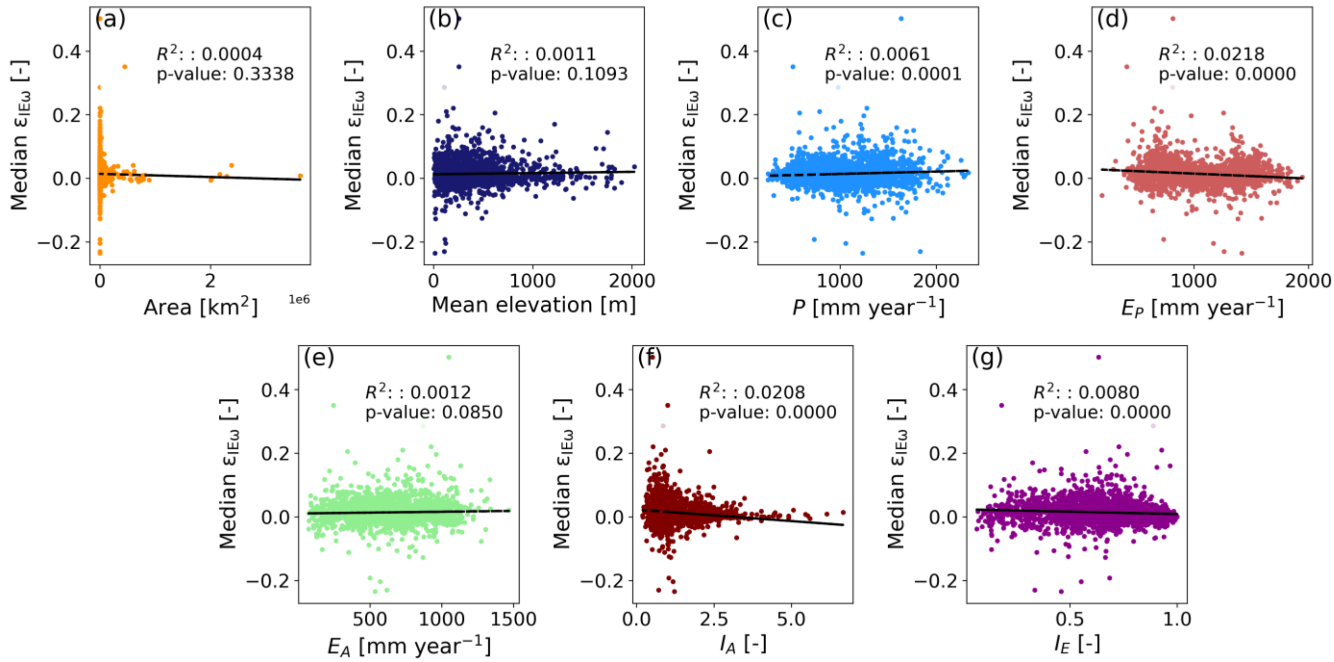

Figure S7: A comparative analysis of median $\varepsilon_{IE\omega}$ in relation to topographic characteristics and climatic indices of study catchments a) Area, b) Mean elevation, c) Precipitation *P*, d) Potential Evaporation E_P, e) Actual Evaporation E_A, f) Aridity Index I_A, and g) Evaporative Index $_{IE}$.

The scatter subplots (Fig. S7a-g), examining the relationship between median deviation $\varepsilon_{IE\omega}$ and topographic characteristics (Area and mean elevation) along with climatic indices of catchments (P, E_P, E_A, I_A, *and* I_E), consistently demonstrate weak or negligible associations. Specifically, the R^2 values are consistently low, ranging from 0.00004 to 0.0218. These values suggest a limited impact by topographic features and climatic indices on the variability of median deviation $\varepsilon_{IE\omega}$. Furthermore, the majority of associated p-values falling below the conventional significance level of 0.05 (Fig. S7c-d,f-g) indicate an overall statistical significance in these relationships. Notably, weak R^2 values and non-significant p-values for topographic characteristics (Area and mean elevation), further highlight the absence of a substantial link with median deviation $\varepsilon_{IE\omega}$. Even in the case of seemingly a bit stronger relationships with climatic indices like P, E_P, I_A, and I_E, statistically significant findings only account for a small fraction of the variability in median deviation $\varepsilon_{IE\omega}$. Both of the R^2

and p-values collectively supports the notion that neither topographic characteristics nor climatic indices exhibit a meaningful relationship with median deviation $\varepsilon_{IE\omega}$ for the analysis in this study.

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