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[*Invited Lecture*]

Hydrological Droughts in the Carpathian Basin: From Historical Evidence to Future Risk under CMIP6 Climate Scenarios

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Abstract: This study extends a multi-index (SPI, STI, SPEI, SDI) assessment of hydrological drought across the Carpathian Basin (1961–2024, 36 stations) with new future projections for the Danube River at the Bezdan station under CMIP6 climate scenarios. Historical analysis shows that precipitation (SPI) has remained largely stationary across the basin, while temperature (STI) has warmed significantly at every station, driving a predominantly water-balance (SPEI) and, in small tributary catchments, hydrological (SDI) drying signal; annual SDI at Bezdan itself shows no trend (Kendall's tau = 0.02). Building on this framework, monthly SDI projections (2025–2050) were generated from three CMIP6 general circulation models (CNRM-ESM2-1, EC-Earth3-CC, IPSL-CM6A-LR), bias-corrected against station records, under SSP1-1.9 and SSP5-8.5. Results show moderate-drought frequency roughly doubling under SSP5-8.5 (9–13%) relative to SSP1-1.9 (3–7%), with a severe episode robustly projected across all three models in mid-2026. Low inter-model correlation underscores persistent structural uncertainty, arguing for multi-model, temperature-aware drought monitoring.

Keywords: hydrological drought; Carpathian Basin; CMIP6 projections; Streamflow Drought Index; SSP scenarios

Introduction

The Carpathian Basin constitutes one of Europe's most climatically and hydrologically sensitive transboundary systems, spanning approximately 300,000 km² across nine countries. Home to more than 30 million people and a major agricultural and hydropower zone, the basin faces escalating water stress from rising temperatures, shifting precipitation seasonality, and more frequent compound heat events (Leščešen et al., 2026). A 64-year (1961–2024), 18-station meteorological and 18-station hydrological record across the basin shows that precipitation (SPI) has remained largely stationary, while temperature (STI) has warmed significantly and pervasively at every station (Leščešen, 2026). A critical insight from this research is that drought intensification is driven predominantly by rising evaporative demand rather than precipitation decline: SPEI, which nets precipitation against evapotranspiration, shows a compounding drying signal concentrated where warming is strongest, and SDI shows this stress beginning to express itself hydrologically in small, less-buffered tributary catchments, even while the Danube and Tisza main stems remain broadly stationary in annual terms. While this body of work establishes a robust historical picture of hydrological drought in the basin, how these dynamics will evolve under future climate change remains comparatively unexplored at the catchment scale. This paper extends the existing multi-index framework forward in time, presenting new monthly Streamflow Drought Index (SDI) projections (2025–2050) for the Danube River at the Bezdan gauging station, driven by three CMIP6 general circulation models under contrasting Shared Socioeconomic Pathways. Combining retrospective trend evidence with forward-looking, multi-model projections provides a more complete evidence base, spanning nearly a century of observed change and a quarter-century of projected futures, to inform transboundary drought early-

warning and water-management planning in a basin where climate and society are tightly, and increasingly precariously, interlinked.

Methods and data

The study integrates two complementary components: (i) a historical multi-index drought assessment covering 1961–2024, and (ii) forward-looking, CMIP6-based SDI projections for 2025–2050 at the Bezdan station on the Danube. Historical analysis draws on a 64-year, 1961–2024 hydrological and meteorological dataset, enabling computation of four standardized indices: SPI (meteorological), STI (thermal stress), SPEI (water balance), and SDI (hydrological). Trend detection used the Mann–Kendall test with Theil–Sen slope estimation; homogeneity was assessed via the Pettitt test; and Self-Organizing Maps (SOMs) enabled spatial regionalisation by trend similarity. For the future projection component, monthly precipitation and near-surface air temperature were obtained for three CMIP6 general circulation models, CNRM-ESM2-1, EC-Earth3-CC, and IPSL-CM6A-LR, accessed via the Copernicus Climate Data Store, for the grid cells overlying Osijek, Sombor, and Pécs, the three meteorological stations used as SDI predictors for Bezdan. Model outputs were bias-corrected against 1961–2024 station records, following established regional practice for CMIP6-based downscaling products. Bias-corrected series were used to compute future SPI, STI, and SPEI, which fed a suite of thirteen candidate regression and machine-learning algorithms (including Random Forest, Support Vector Regression, XGBoost, LightGBM, and LSTM) trained on 1961–2024 data to predict SDI at Bezdan; model selection combined cross-validated error metrics (MAE, RMSE, R^2 , NSE, KGE) into a composite ranking. The selected model generated monthly SDI projections for 2025–2050 under two contrasting Shared Socioeconomic Pathways (O'Neill et al., 2017): SSP1-1.9, a strong-mitigation, Paris-Agreement-aligned trajectory, and SSP5-8.5, a high-emission, fossil-fuel-intensive

pathway, following the CMIP6 experimental design (Eyring et al., 2016).

Results and discussion

Over the 1961–2024 observation period, meteorological drought (SPI) across the 18-station network remained essentially stationary: 17 of 18 stations show no significant Mann–Kendall trend, with Budapest the sole exception ($Z = -2.312$, $p = 0.021$). By contrast, the Standardised Temperature Index (STI) warmed unambiguously and significantly at all 18 stations (Z from 6.8 to 14.8, $p \approx 0$), with Sen's slopes of 0.0012–0.0023 STI units/month and abrupt Pettitt change points clustering in the late 1990s to early 2000s. SPEI, which nets precipitation against evapotranspiration, shows a mixed but predominantly drying signal: significant decreasing trends at 6 of 18 stations (Budapest strongest, $Z = -4.325$; also Bjelovar, Zrenjanin, Szombathely, Sremska Mitrovica, and Debrecen), concentrated where warming is strongest. SDI, the hydrological index, shows that this thermally-driven water-balance stress is beginning to express itself hydrologically in small, less-buffered tributary catchments (Čatež on the Sava; Brehy and Holiša in Slovakia), while the Danube and Tisza main stems, including Bezdan, remain broadly stationary in annual terms. At Bezdan specifically, annual SDI shows no trend over 1961–2024 (Kendall's tau = +0.02, $p = 0.792$), effectively the flattest signal of any Danube main-stem station, consistent with its position as an integrative gauge downstream of a large, heterogeneous catchment. Its three meteorological predictor stations, Osijek, Sombor, and Pécs, mirror the basin-wide asymmetry precisely: none shows a significant trend in SPI or SPEI, yet all three show highly significant STI warming (Osijek $Z = 10.4$; Sombor $Z = 11.3$; Pécs $Z = 10.2$; all $p \approx 0$). This predictor-station profile, stable precipitation and net water balance, but unambiguous warming, sets the empirical baseline against which the future SDI projections for Bezdan are read. Projecting forward,

monthly SDI at Bezdan (2025–2050) was generated from three CMIP6 GCMs bias-corrected against the Osijek/Sombor/Pécs 1961–2024 record, under SSP1-1.9 and SSP5-8.5. Under SSP1-1.9, moderate-drought frequency (SDI < -1.0) ranges from 3.2% to 6.5% of months across the three models, broadly consistent with the historically stationary Bezdan SDI record. Under SSP5-8.5, moderate-drought frequency rises to 9.0–12.6%, roughly double, and all three models independently converge on a severe drought episode in mid-2026, with SDI reaching as low as -2.08. This projected intensification reads as a forward extension of the historical asymmetry documented above: precipitation at the Bezdan predictor stations has not systematically declined, but temperature has warmed significantly at all three, and it is this same evaporative-demand mechanism, not an assumed future decline in rainfall, that the SSP5-8.5 projections implicitly encode through elevated temperatures cascading into more frequent SPEI-driven deficits and, ultimately, higher projected SDI drought frequency at Bezdan. Near-zero pairwise correlation between models ($r < 0.10$ in all cases) indicates persistent structural uncertainty in the timing of individual future episodes, even as the models agree directionally that the low-flow regime historically stable at Bezdan through 2024 is projected to become measurably less stable under higher-emission futures, a genuinely new signal relative to the stationary historical record, and one that argues for SPEI-centred, ensemble-based monitoring rather than reliance on any single GCM or index.

Conclusions

Six decades (1961–2024) of multi-index hydrological evidence and a quarter-century of CMIP6-based projections converge on the same central finding for the Carpathian Basin: rising evaporative demand, not precipitation decline, is the primary driver of intensifying drought. Precipitation (SPI) remains stationary at 17 of 18 stations, while

temperature (STI) has warmed significantly at all 18, and SPEI and SDI both show this asymmetry compounding into water-balance and, in small tributary catchments, hydrological drought, even as annual SDI at Bezdan itself, and along the Danube and Tisza main stems more broadly, remains statistically stationary. This same asymmetry is encoded in the future projections: moderate-drought frequency at Bezdan roughly doubles under SSP5-8.5 relative to SSP1-1.9, and all three CMIP6 models, despite otherwise limited agreement, converge on a severe drought episode in mid-2026, flagging a concrete near-term risk window for transboundary water management on the Danube. Persistent structural uncertainty between GCMs, and the historically stationary annual SDI signal at Bezdan itself, argue against reliance on any single model, station, or index. Multi-index, multi-model, temperature-aware drought monitoring and forecasting frameworks, integrating both retrospective trend evidence and forward-looking ensemble projections, constitute the most robust operational basis for anticipating and managing hydrological drought risk across the Carpathian Basin's shared river systems.

References

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