Persistence of hydrometeorological droughts in Slovakia: A multi-season discharge anomalies analysis using Markov Chains

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INTRODUCTION

- Climate warming is intensifying hydrological extremes, increasing the risk of prolonged droughts across Central Europe.

- Slovakia has experienced recurrent multi-year droughts in recent decades, particularly in lowland basins.

- Traditional drought analyses neglect persistence ("hydrological memory") and clustering of dry seasons.

- Markov-chain models provide a probabilistic framework to quantify drought duration and persistence.

- This study delivers the first national-scale assessment of multi-season drought persistence in Slovakia.
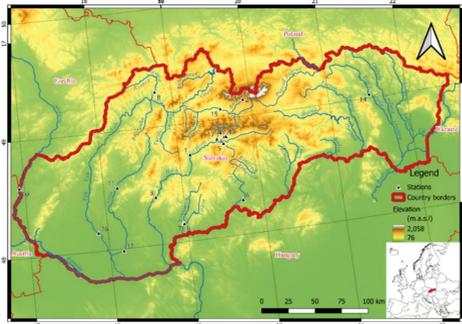

Fig. 1. Study area

RESULTS

Fig. 2. Drought persistence (Pdd vs. Pww)

Fig. 3. Longest observed drought spells
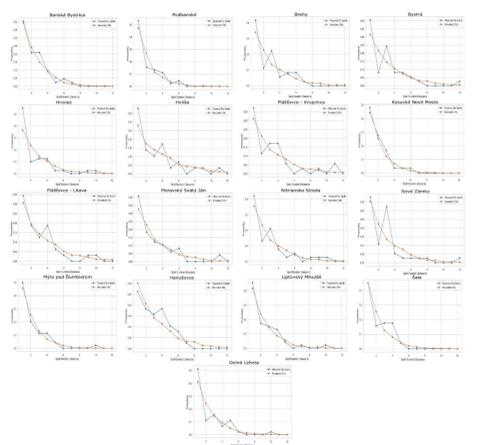
Fig. 4. Observed vs. Markov-simulated drought durations

Fig. 5. Decadal drought risk (5–10 years).

METHODS

- Analysed long, near-natural discharge records (mostly 1928–2023) from 17 Slovak gauging stations.

- Daily flows aggregated to winter (Oct–Mar) and summer (Apr–Sep) half-year seasons.

- Seasonal discharge anomalies computed relative to the 1961–1990 reference period.

- Seasons classified as dry (negative anomaly) or wet (non-negative anomaly).

- Estimated dry-to-dry (Pdd) and wet-to-wet (Pww) transition probabilities.

- Applied first-order two-state Markov chains and generated long synthetic sequences.

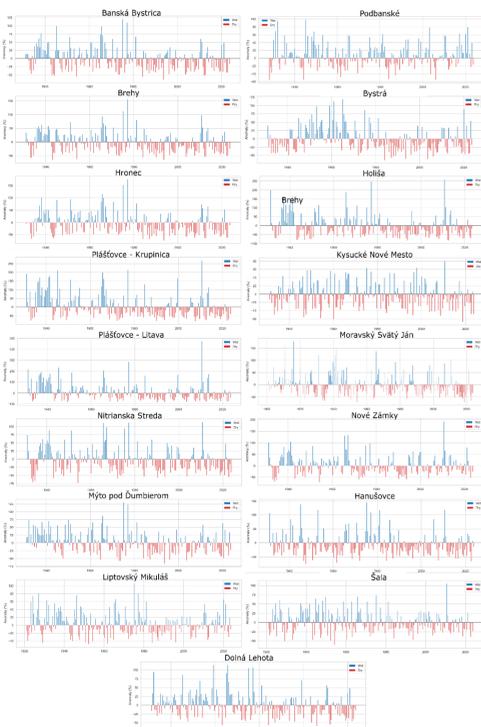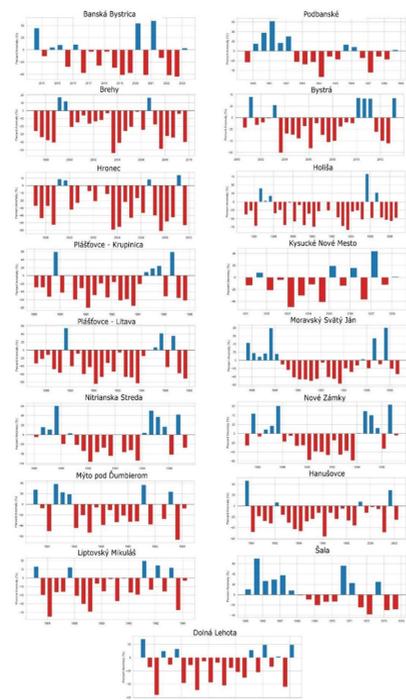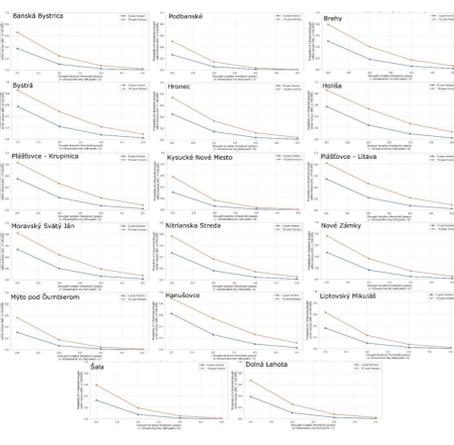- Simulated 100-year drought extremes and 5–10 year drought exceedance probabilities.

RESULTS

- **Drought persistence dominates over wet persistence:** Dry-to-dry transition probabilities (Pdd) exceed wet-to-wet probabilities (Pww) at most stations, indicating that once drought conditions are established, they tend to persist longer than wet conditions, especially in lowland basins (Fig. 2).

- **Strong spatial control by basin characteristics:** Drought persistence increases with basin size, low elevation, and continentality, reflecting the integration of large-scale atmospheric circulation anomalies and long hydrological memory in lowland catchments (Fig. 2).

- **Contrasting drought behavior across elevations:** Mountain headwaters experience shorter but often more intense drought spells, while lowland rivers exhibit long-lasting, multi-season droughts driven by groundwater storage and delayed recovery (Fig. 3).

- **Observed droughts reach near-rare persistence levels:** Several basins already show drought durations approaching near-centennial persistence, highlighting that extreme hydrological droughts are not merely future projections but are already evident in observations (Fig. 3).

- **Markov models capture statistical persistence:** First-order Markov chains successfully reproduce the observed distribution of multi-season drought durations across contrasting catchments, confirming persistence as a key statistical feature of streamflow droughts (Fig. 4).

- **Limitations of stochastic modeling:** While effective statistically, Markov models cannot resolve the physical drivers of persistence and systematically underestimate wet-spell persistence, indicating asymmetric hydrological memory favoring dry states (Fig. 4).

- **High decadal drought risk in lowlands:** Simulations reveal a substantial probability of 3–5-year droughts within a single decade, particularly in southern and western lowland basins, posing significant challenges for water resources management (Fig. 5).

- **Consistency with long-term evidence:** The results align with documentary records and proxy-based reconstructions of prolonged droughts in Central Europe, suggesting that current patterns reflect both natural variability and warming-enhanced evapotranspiration (Figs. 2–5).

CONCLUSION

- Multi-season drought persistence in Slovakia is well described by first-order Markov chains.

- Drought behaviour differs fundamentally between alpine headwaters and lowland rivers.

- Lowland basins face a tangible risk of multi-year droughts within typical planning horizons.

- Historical records may underestimate the full range of possible drought durations.

- Results provide actionable probabilistic metrics for water management and drought planning.

- Incorporating persistence is essential for climate adaptation in Slovak river basins.

KEY TAKE-HOME MESSAGES

1. **Droughts in Slovakia persist over multiple seasons, not isolated events:** Hydrological droughts commonly cluster across several consecutive half-years, especially in lowland basins, revealing strong system memory that is missed by traditional frequency analyses.

2. **Lowland rivers are far more vulnerable to long-lasting droughts than mountain headwaters:** While alpine catchments experience high variability, the most persistent droughts (up to 13–19 seasons) occur in southern and western lowland basins with high dry-to-dry persistence.

3. **Simple Markov-chain models reliably quantify drought duration and risk:** First-order Markov chains successfully reproduce observed drought spell lengths and allow estimation of rare events beyond the instrumental record, including 100-year droughts.

4. **Multi-year droughts are plausible within decadal planning horizons:** Simulations indicate substantial probabilities of 3–5-year droughts within the next decade, posing serious challenges for water supply, ecosystems, and reservoir management under ongoing warming.

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