TEMPORAL SHIFTS IN SEASONAL LOW FLOWS: UNRAVELLING CLIMATE-DRIVEN HYDROLOGICAL RECONFIGURATION IN THE CARPATHIAN BASIN

ÚSTAV HYDROLÓGIE SAV, v. v. i.
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Introduction

- Rivers of the Danube–Carpathian system are undergoing rapid climate-driven change, with warming trends and seasonal precipitation redistribution reshaping hydrological regimes.
- Snow-related processes are weakening, with earlier melt and declining snowpack reducing summer baseflow, while rising evapotranspiration intensifies soil moisture depletion and low flow severity.
- Beyond magnitudes, climate change alters the timing of seasonal low flows: earlier minima in snow-dominated catchments, and later summer/autumn minima in lowland basins under strong evaporative demand.
- Observations since 2010 confirm that regime reconfiguration is already underway, with shorter and more intense low flow periods, increased runoff variability, and unsynchronised minima across sub-basins.
- Despite extensive research on floods and droughts, the timing of low flows remains underexplored in the Carpathian Basin, limiting adaptive water management in this transboundary system.

Study area and metohds

- The Carpathian Basin in Central and Eastern Europe is defined by the interplay of mountain headwaters, extensive lowlands, and a highly interconnected transboundary river network dominated by the Danube.
- Draining more than 800,000 km² across ten countries, the basin supports over 80 million people with vital ecosystem services, freshwater resources, agriculture, hydropower, and navigation.
- This study analyses daily discharge records from 1931–2020 at 16 hydrometric stations spanning the Danube main stem and major tributaries, including the Tisza, Sava, Nitra, Hron, and Samos (**Fig. 1**).
- The dataset represents diverse hydrological regimes, from snow-influenced headwaters to pluvial lowlands, capturing the basin's spatial heterogeneity.
- Records were compiled from national hydrological archives and the International Commission for the Protection of the Danube River (ICPDR), with all series subjected to standardised quality control to ensure consistency.
- Kernel density estimation (KDE) was applied to annual minimum flow dates, allowing the assessment of both central tendencies and variability in seasonal low flow timing.
- The long-term, high-resolution dataset provides a robust basis for detecting temporal shifts in low flow occurrence and for comparing regime-specific responses to climate forcing.

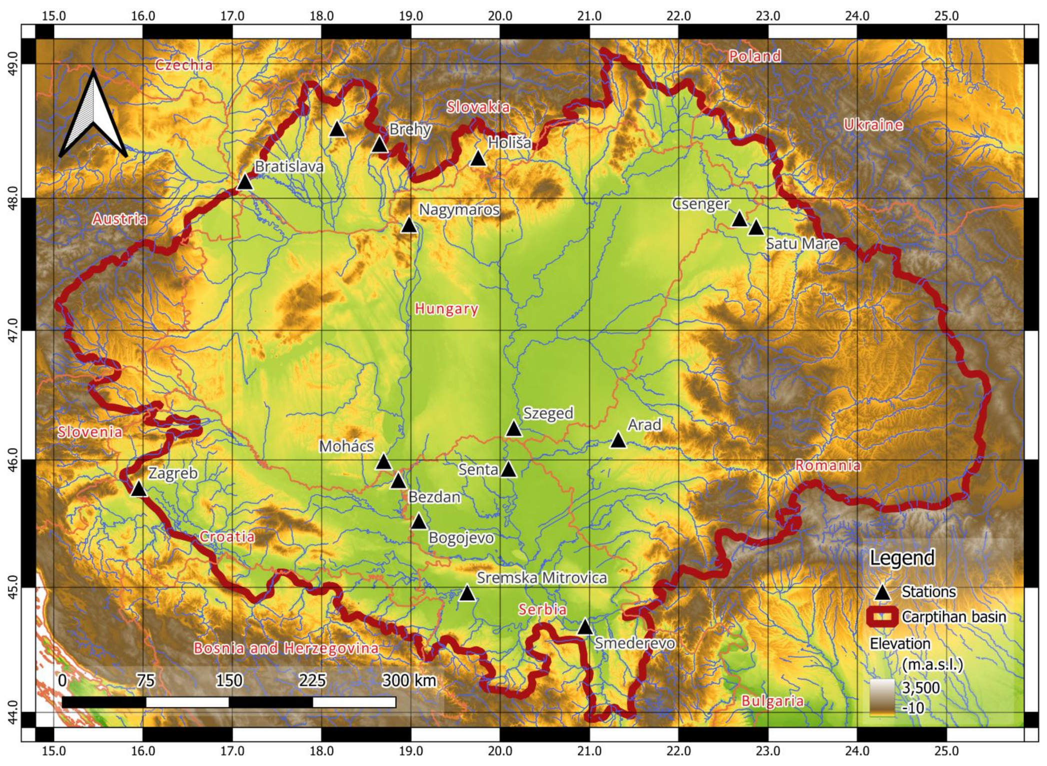

Fig. 1. Location of the selected gauging stations on the map of Carpathian basin.

Results and discussion

- Spring minima are delayed by 15–20 days in large rivers (Danube, Tisza), while smaller tributaries show more modest 5–10-day shifts (**Fig. 2**).
- Elevation and snowmelt dynamics strongly influence spring delays, with higher-elevation headwaters storing winter precipitation longer.
- Summer minima shift later by 20–30 days, driven by evapotranspiration losses, drought, and reduced rainfall rather than snow processes (**Fig. 3**).
- Seasonal divergence emerges: spring delays are moderated by cryospheric buffering, whereas summer delays are amplified by atmospheric forcing.

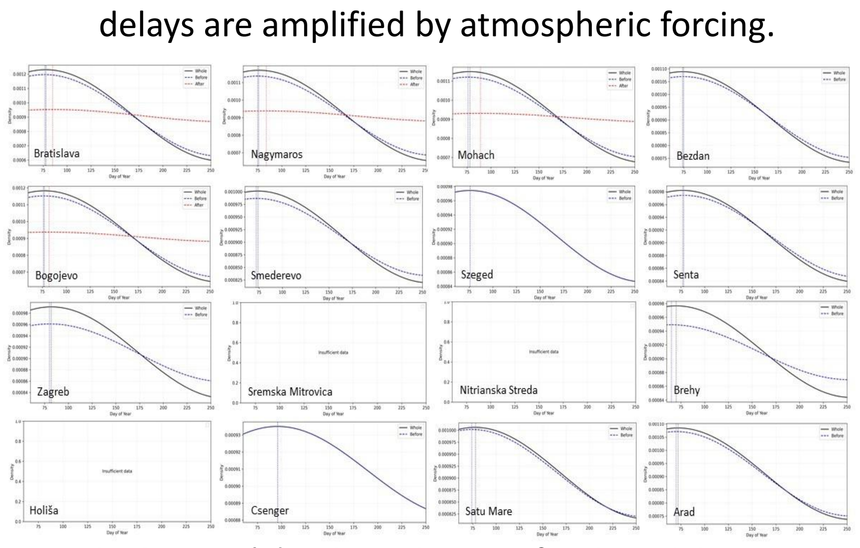

Fig. 2. Kernel density estimates of spring minimum discharge dates.

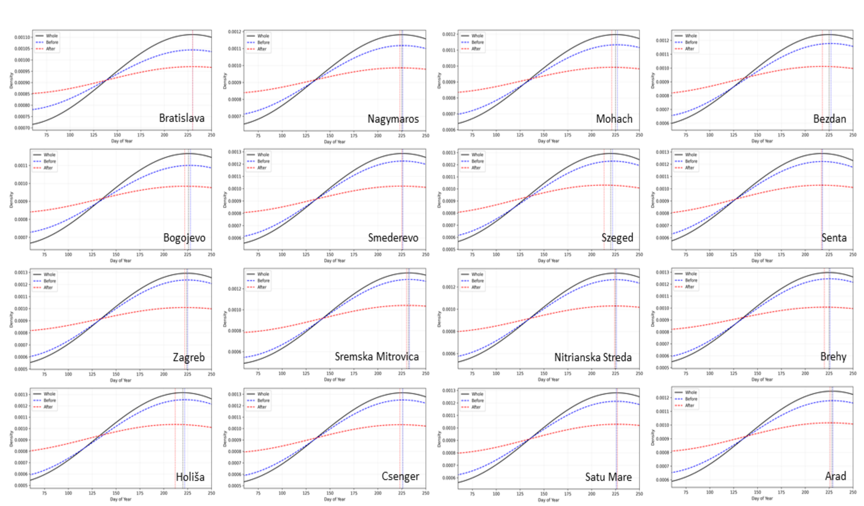

Fig. 3. Kernel density estimates of summer minimum discharge dates.

- Upper Danube stations show 10–25% reductions in minimum flows, reflecting strong sensitivity to basin-scale hydroclimatic change.
- Middle Danube stations exhibit greater variability and a higher likelihood of extreme low flows due to combined climatic and anthropogenic pressures.
- The Tisza and Sava basins reveal bimodal or compressed distributions, highlighting drought sensitivity and the role of catchment size in modulating flow variability.
- Small tributaries (Nitra, Hron, Ipeľ) show sharp declines up to 40%, while eastern basins display mixed responses ranging from minimal reductions to 35% declines (**Fig. 4**).

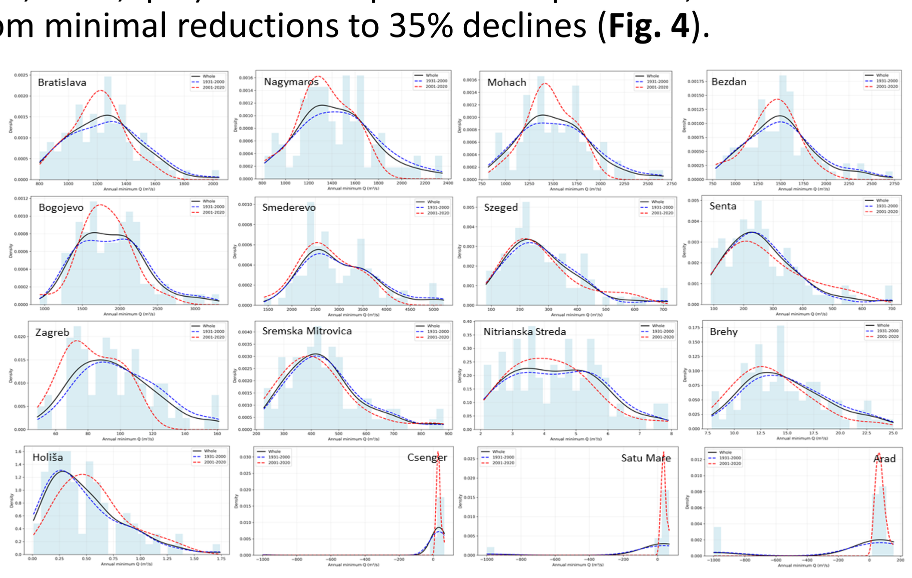

Fig. 4. Kernel density estimates of annual minimum discharges at selected gauging stations.

Results and discussion

- **Fig. 5** shows shifts of -30 to +60 days in low-flow timing across the Carpathian Basin.
- Western stations (e.g., Bratislava, Nagymaros) exhibit spring delays of 10–20 days due to extended snowmelt.
- Eastern stations (e.g., Satu Mare, Csenger) record advances of up to -19 days, linked to earlier soil moisture depletion.
- Smaller tributaries in Figure 5 show high variability (-30 to +30 days), reflecting sensitivity to local climate.
- The Danube, Tisza, and Sava display consistent 0–20 day delays, tied to evapotranspiration and atmospheric drivers.
- Figure 6 shows summer timing shifts mainly between -10 and +10 days.
- Western and central sites (e.g., Bratislava, Nagymaros) reveal slight summer delays of 2–6 days.
- Eastern Tisza stations (Szeged, Senta) show longer summer delays (+7 to +10 days), indicating higher drought stress.
- In **Fig. 6**, lowland sites (<100 m a.s.l.) exhibit uniform small delays, while higher elevations display more variability.
- Comparing Figures 5 and 6 highlights seasonal asymmetry: large spring shifts versus smaller but consistent summer delays.

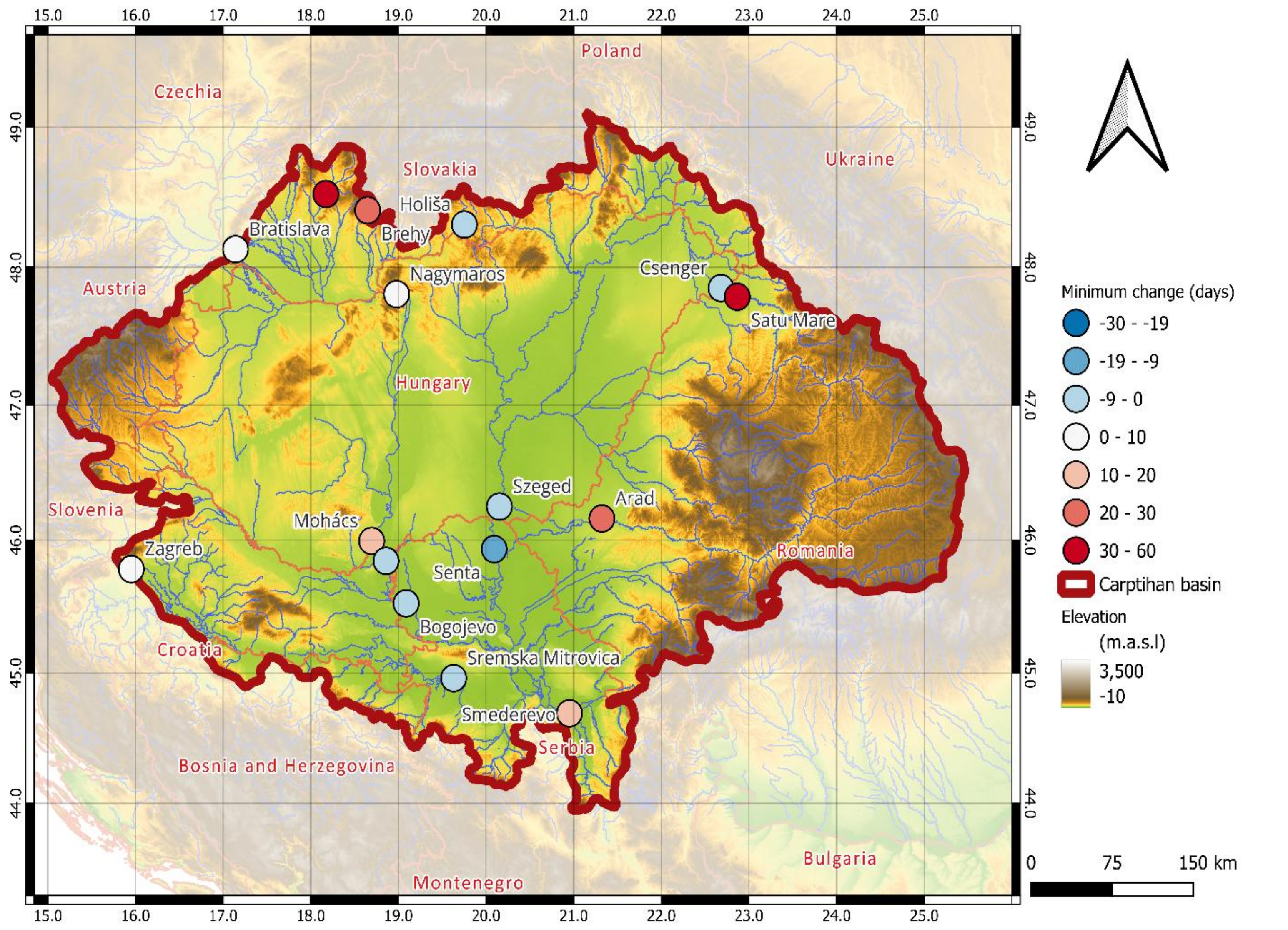

Fig. 5. The differences (in days) in the timing of occurrence of minimum discharges in spring. Blue color indicates earlier and red color later occurrence of peak discharge.

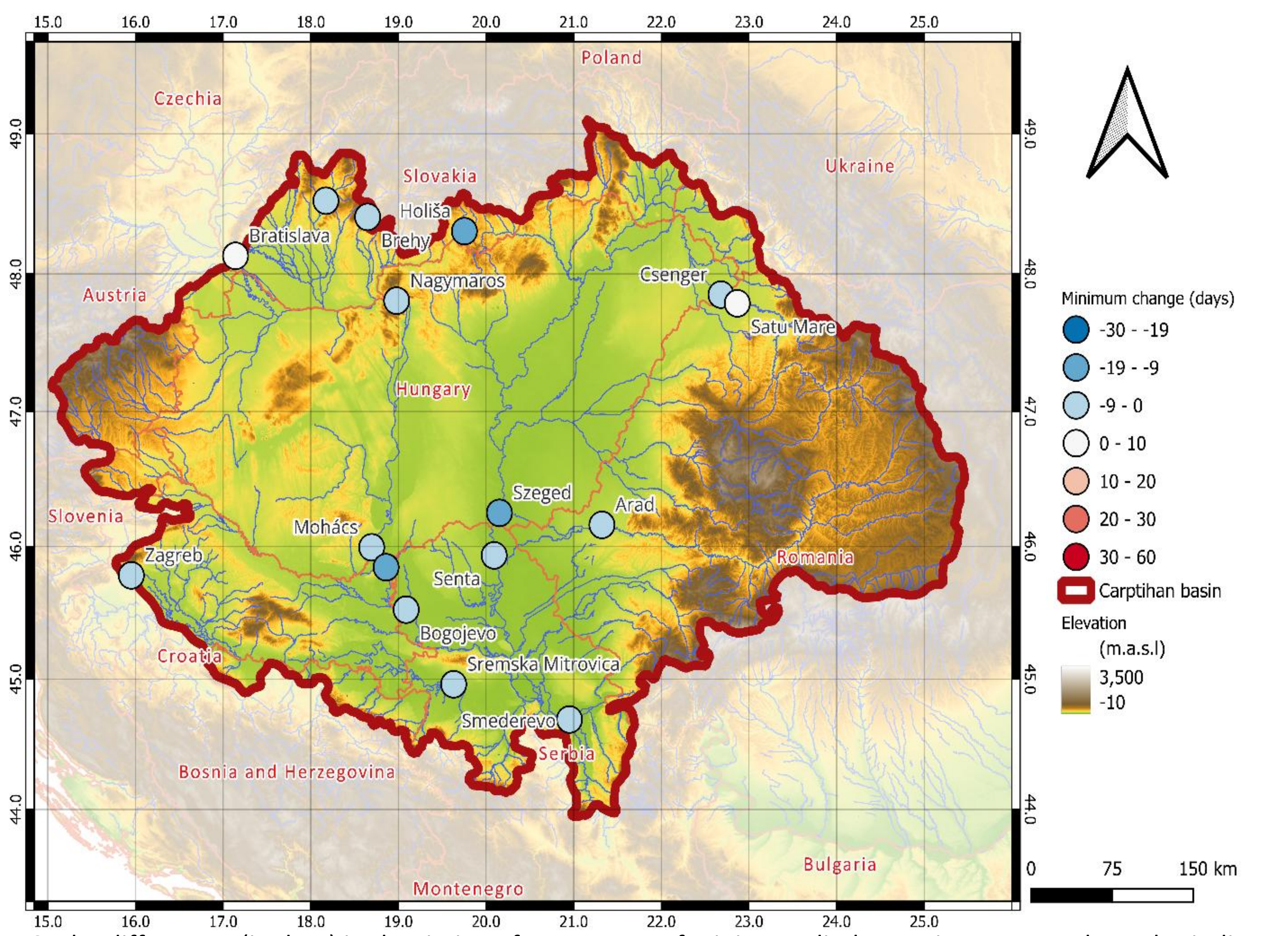

Fig. 6. The differences (in days) in the timing of occurrence of minimum discharges in summer. Blue color indicates earlier and red color later occurrence of peak discharge.

Conculsion

- Low water regimes in the Danube and its tributaries have changed due to climate change and human intervention.
- Minimum flows declined by 10–40%, especially in summer, indicating intensified drought conditions.
- Rain-fed sub-basins like the Tisza show bimodal distributions and high vulnerability to precipitation deficits.
- Spring minima are delayed in mean timing but show earlier modal peaks, reflecting reduced snowmelt influence.
- Summer minima occur earlier in the year but with delayed density peaks, indicating prolonged drought spells.
- Ecological impacts include threats to biodiversity, habitats, and floodplain connectivity, while economic sectors face risks to navigation, hydropower, and agriculture.
- Transboundary drought effects demand stronger cooperation through bodies like the ICPDR.
- Future research should integrate CMIP6 modeling, remote sensing, and socio-hydrological scenarios to support adaptation and resilience.

DroughtThruTime

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