Landscape heterogeneity and spatial and temporal patterns of river water quality – a stochastic modelling approach

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Motivation

Problem

- Worldwide degradation of river water quality
- Where and when to measure in poorly and ungauged catchments?
- Lacking understanding of spatial scales and origin of spatiotemporal variability

Analysis

- Explorative modelling of landscape-scale solute export processes
- Identification of drivers and controls of space-time variance of water quality at the macro-scale

Goal

- Examination of useful concepts and metrics to quantify space-time variance in and along river networks
- Inform water quality monitoring networks to effectively capture overall spatiotemporal variability

Stochastic Modelling Approach

1. Subcatchment-scale distribution of solute source zones	
Structured solute source zone heterogeneity	γ_{sc}
Random solute source zone heterogeneity	σ_{sc}
2. Macro-scale landscape configuration	
Structured macro-scale heterogeneity	γ_{ma}
Random macro-scale heterogeneity	σ_{ma}
3. Hydroclimatic forcing	
Interarrival-time of Poisson time series	λ_d
Hydrologic inter-subcatchment synchrony	ϕ_{hyd}

$$c_{im}(\tau) = \tau^{\gamma} W \text{, with } \sigma^2_{lnW}$$

where τ is the travel time from solute source to the stream, γ is a non-linear correlation coefficient and W is a lognormal random variable with variance σ^2.

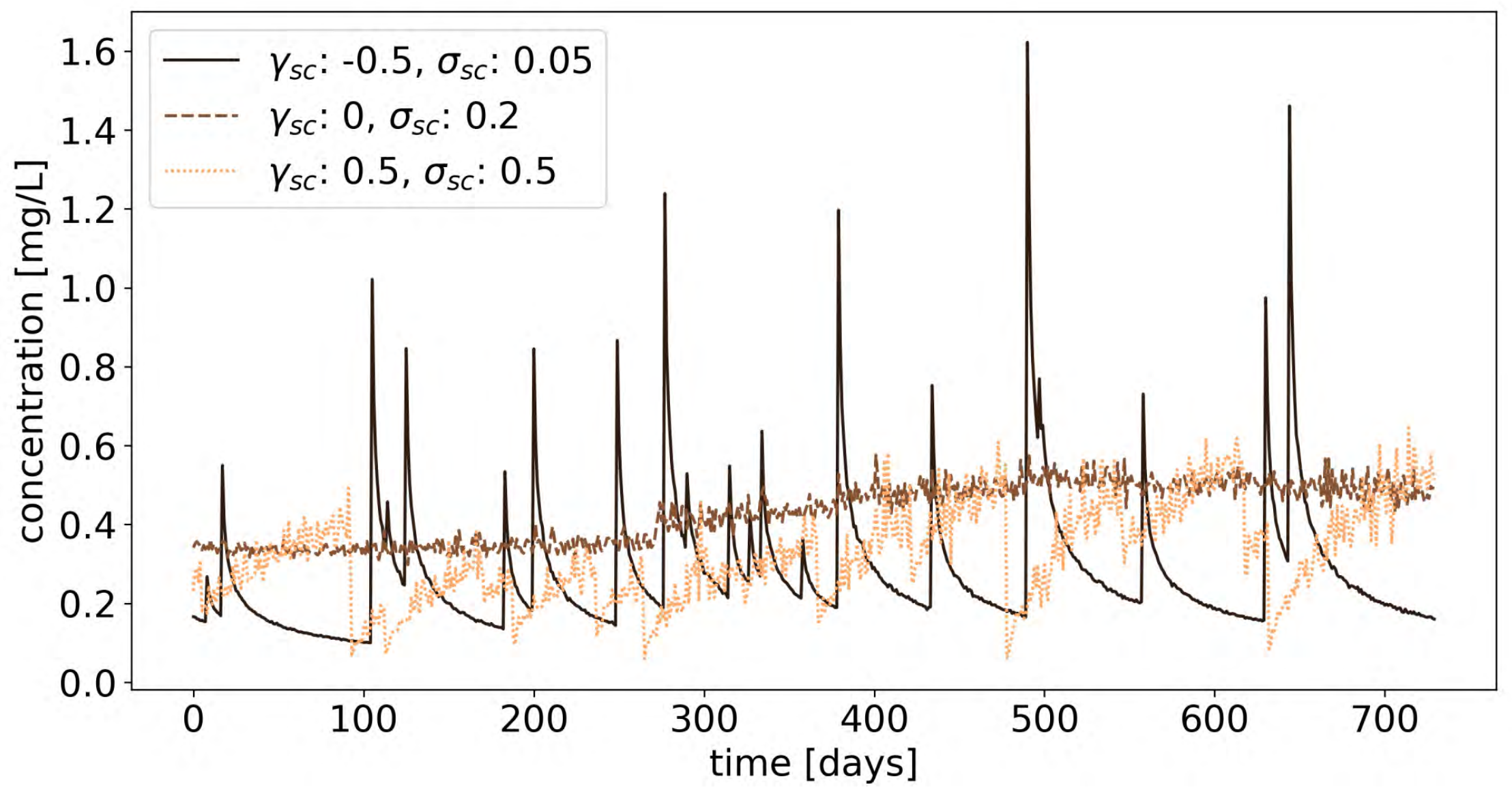

Figure 1: Exemplary time series for different parameterizations of the subcatchment-scale distribution of solute source zones. A negative γ_{sc} implies solute source zones are clustered near the stream, whereas positive γ_{sc} implies solute source zones are predominantly far away from the stream. Original model: Musolff et al. (2017).

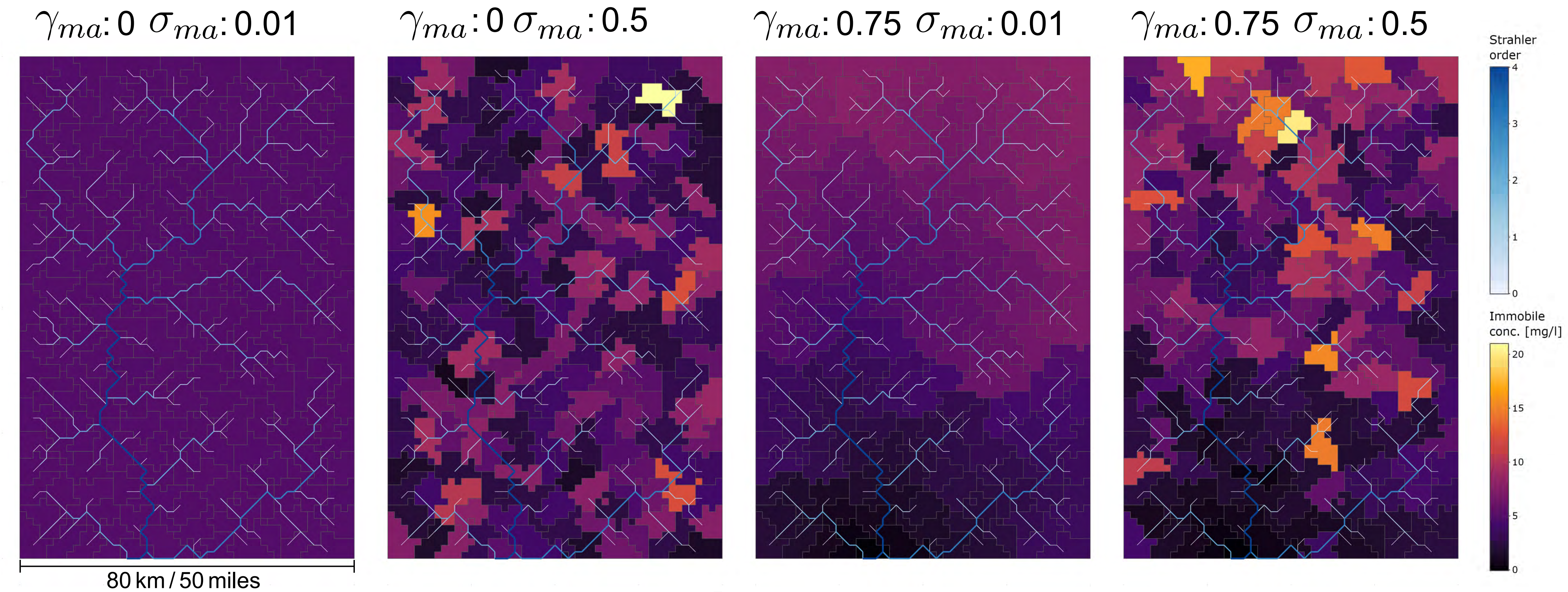

Figure 2: Different parameterizations of structured (γ_{ma}) and random (σ_{ma}) macro-scale landscape heterogeneity in the form of immobile concentration at the subcatchment-scale. Calculation of the subcatchment immobile concentration is based on the distance to outlet.

Quantification of target metrics

1. $\overline{CV_s} = \frac{1}{n_i} \cdot \sum_{i=1}^{n_i} \frac{\sigma_{X_i}}{\mu_{X_i}}$
2. $\overline{CV_t} = \frac{1}{n_j} \cdot \sum_{j=1}^{n_j} \frac{\sigma_{X_j}}{\mu_{X_j}}$

X is the space-time matrix of n_j streams and n_i number of daily values, σ is the standard deviation and μ is the mean.

3. Sychrony: see Hammond and Kolasa (2014)
4. Spatial stability: see Gu et al. (2021)

Model Evaluation

- Global sensitivity analysis: Morris method
- Number of trajectories: 30
- Number of parameters: 6
- Total number of simulations: 210

Results

- Simulated $\overline{CV_s}$ ranged considerably and decreased with increasing stream order
- $\overline{CV_t}$ was similar to observed values and was largely preserved along the river network
- Spatial stability and synchrony were high and increased with increasing stream order

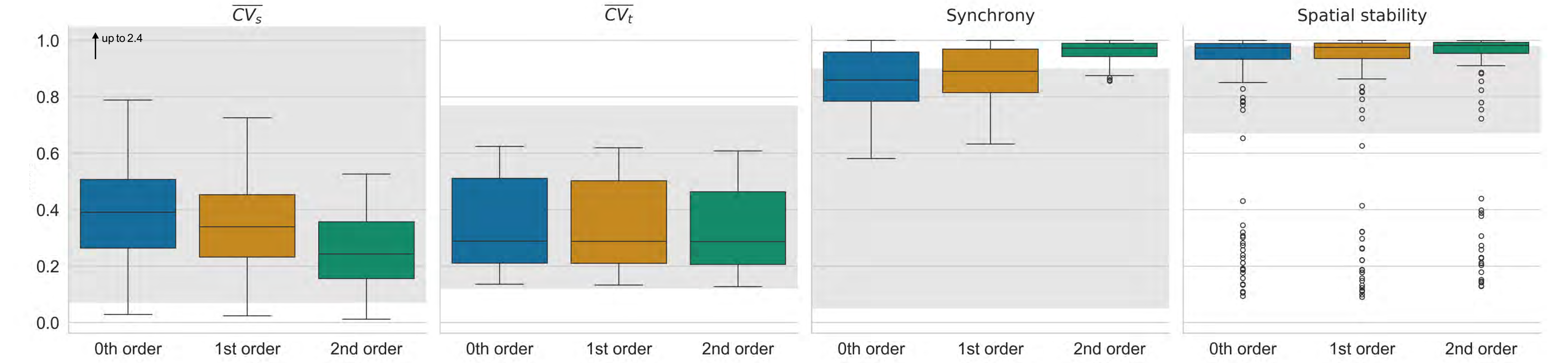

Figure 3: $\overline{CV_s}$, $\overline{CV_t}$, synchrony and spatial stability of the 210 simulation runs. Analysis was based on the position in the river network for 0th, 1st and 2nd order streams. Grey areas indicate observations from own analysis of water quality in Germany and results from Gu et al. (2021) and Dupas et al. (2019).

- Macro-scale landscape configuration regulated $\overline{CV_s}$ and spatial stability of solute concentration and importance of structured and random macro-scale heterogeneity changed with network position
- $\overline{CV_t}$ and synchrony are regulated at the subcatchment-scale and by the spatial synchrony of hydroclimatic forcing

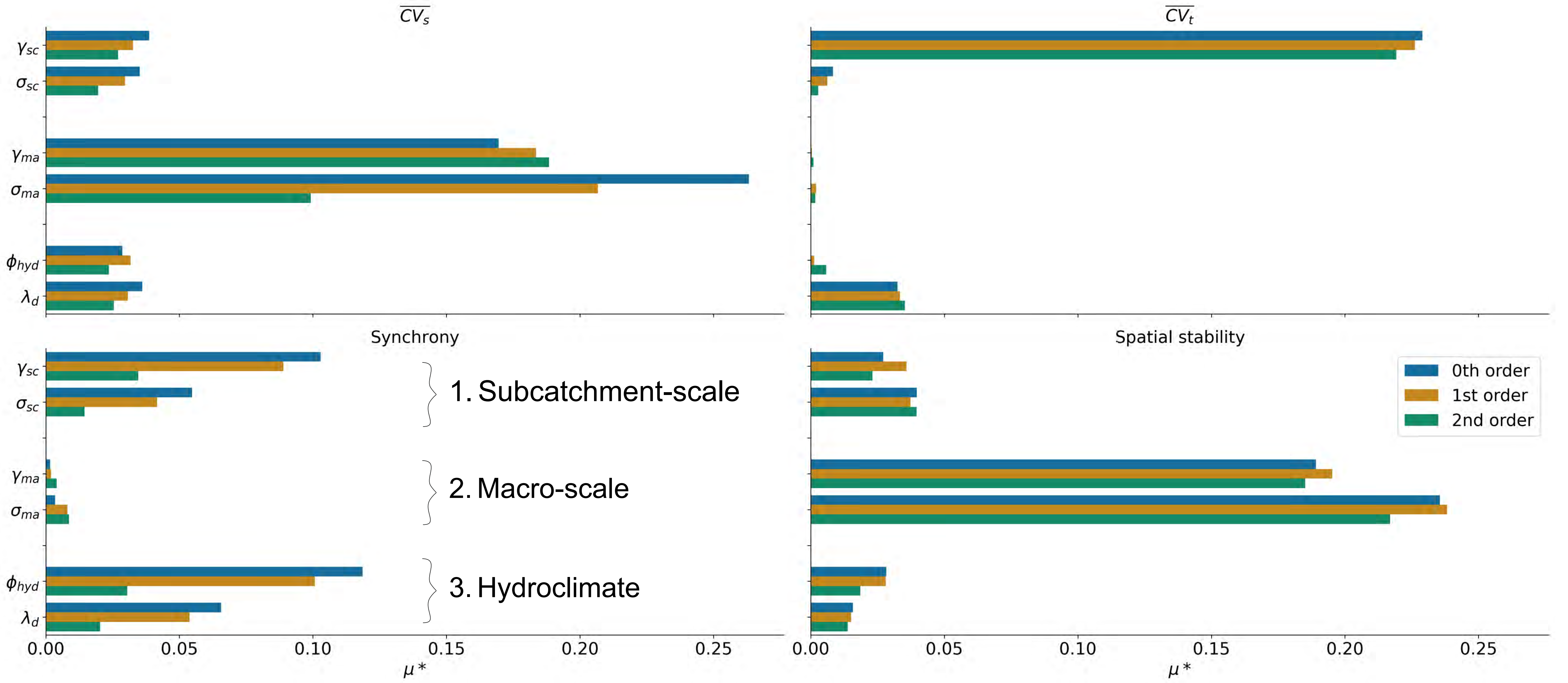

Figure 4: Mean absolute elementary effects (μ*) from Morris method for $\overline{CV_s}$, $\overline{CV_t}$, synchrony and spatial stability for three dimensions of controlling variability. 1. subcatchment-scale: γ_{sc} and σ_{sc}, 2. macro-scale landscape configuration: γ_{ma} and σ_{ma} and 3. hydroclimatic forcing: ϕ_{hyd} and λ_d.

Conclusion

- Spatial and temporal variability originate from controls at different spatial scales, which can inform the design of water quality monitoring networks
- Spatial stability of solute concentration is primarily a function of macro-scale random and structured landscape heterogeneity
- Spatial synchrony is regulated by processes at the subcatchment scale and hydroclimatic forcing

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