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Brief communication: Anomalous low-discharge conditions increase algal bloom risk in Central European rivers

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Abstract. Hydrological extremes have significant implications for riverine eutrophication as evidenced by algal (phytoplankton) blooms in European rivers during recent drought years. To assess how discharge conditions modulate nutrient-induced phytoplankton growth, we systematically analyze multi-year discharge, total phosphorus, and phytoplankton-indicating chlorophyll a data from 30 monitoring sites across Germany. We show that negative discharge anomalies consistently correspond to positive anomalies in measured chlorophyll a relative to the maximum possible chlorophyll a at the given phosphorus level. Further, we found increased algal bloom risk under below-normal discharge conditions, underlining the future challenges for water quality and eutrophication management under intensifying hydrological extremes.

1 Introduction

The frequency and intensity of hydrological extremes including both floods and droughts have significantly increased in Central Europe (Rakovec et al., 2022; Fang et al., 2024). Droughts affect river water quality, as low-discharge conditions modify the export, retention, and in-stream processing of nutrients (Van Vliet et al., 2023; Saavedra et al., 2024). Moreover, droughts can boost blooms of pelagic (i.e., phytoplankton) and benthic algae (e.g., Paerl and Otten, 2013; Van Vliet et al., 2023) - typical manifestations of eutrophication, the overproduction of biomass in water bodies due to nutrient enrichment (e.g., Le Moal et al., 2019).

Algal (phytoplankton) blooms are a threat to clean water supply and aquatic ecosystem functioning through fish kills, oxygen depletion, the release of toxins, and biodiversity loss (e.g., Le Moal et al., 2019). Key mechanisms beyond nutrients promoting critical phytoplankton growth during droughts include increased water residence time (e.g., Reynolds, 2000), enhanced light availability from reduced turbidity and water depth (Julian et al., 2008; Kamjunke et al., 2021), and higher temperatures favoring phytoplankton growth (Paerl and Otten, 2013). However, intensified grazing by benthic filter-feeders under low discharge and high temperatures may counteract these effects in some cases (Lei et al., 1996; Pigneur et al., 2014).

As droughts are projected to become longer and more intense across Central Europe (Rakovec et al., 2022), related water quality issues are likely to intensify (Van Vliet et al., 2023). During recent drought years, atypical phytoplankton blooms occurred in major European rivers such as the Moselle, Elbe, and Oder, including summer blooms in rivers that typically exhibit only spring phytoplankton peaks (Kamjunke et al., 2021; Kleinteich et al., 2024; Köhler et al., 2024). Some of these summer blooms were dominated by toxin-producing, heat-tolerant cyanobacteria or brackish-water algae with competitive advantages under high temperatures or multiple stressors (Paerl and Otten, 2013; Kleinteich et al., 2024; Köhler et al., 2024). Yet, these episodic bloom events contrast with long-term declines in riverine phytoplankton biomass over recent decades, mainly due to lower nutrient inputs - particularly phosphorus from wastewater sources (Westphal et al., 2019; Minaudo et al., 2021) - and the invasive spread of benthic filter-feeders (Minaudo et al., 2021). Given these counteracting dynamics, it remains uncertain whether extreme droughts consistently lead to enhanced riverine phytoplankton concentrations and more frequent bloom situations across different rivers. This uncertainty calls for a quantitative assessment of drought–phytoplankton relationships across spatial and temporal scales.

To address this need, we analyze a multi-year dataset of discharge (Q), total phosphorus (TP), and chlorophyll a (Chl-a, as a proxy for phytoplankton biomass) from 30 river monitoring sites across Germany. To separate the effect of declining TP from hydrological variability, we employ the degree of realized eutrophication ($\alpha_{realized}$), a metric introduced by Hubig et al. (2025) that quantifies how efficiently riverine phytoplankton utilizes the available TP. To investigate how discharge anomalies relate to $\alpha_{realized}$, we quantify deviations of Q and $\alpha_{realized}$ from their typical seasonal conditions for each station and evaluate their relationships across sites and seasons. Finally, we assess potential ecological implications by quantifying phytoplankton bloom frequencies under relatively low- and high-discharge situations.

2 Material and Methods

2.1 Discharge and water quality dataset

This study employs a dataset of Q, TP, and Chl-a monitoring data from 30 river sites across Germany. It is based on a water quality dataset compiled from data provided by the German federal environmental authorities, which was introduced by Hubig et al. (2025) and further modified by Hubig et al. (2026). Most of these data stem from the QUADICA database providing water quality and quantity observations for Germany (Ebeling et al., 2022, 2026). Q data represent daily averages, while TP and Chl-a data were obtained from grab samples. Hubig et al. (2025) included measurement dates with simultaneous TP and Chl-a data, further excluding the dormant winter months (December, January, February) and years before 2000. Hubig et al. (2026) applied stricter criteria regarding seasonal coverage, only accepting years with at least nine measurements between March and November.

Here, we added two further constraints: Q data must be available and each station must cover at least five valid years. Finally, this resulted in 255 sample years across 30 stations in Germany (Figure 1). The median duration per station is seven years, with a maximum of fifteen years. The dataset spans 2000–2019, with a median of 14 active stations per year. Following Hubig et al. (2026), we standardized the measurement frequency by interpolating the data to nine fixed reference days per year, spaced evenly at 29-day intervals. In the following, we refer to the evenly spaced time series of Q, TP, and Chl-a as monthly data, emphasizing that each data point represents a discrete observation rather than a monthly average.

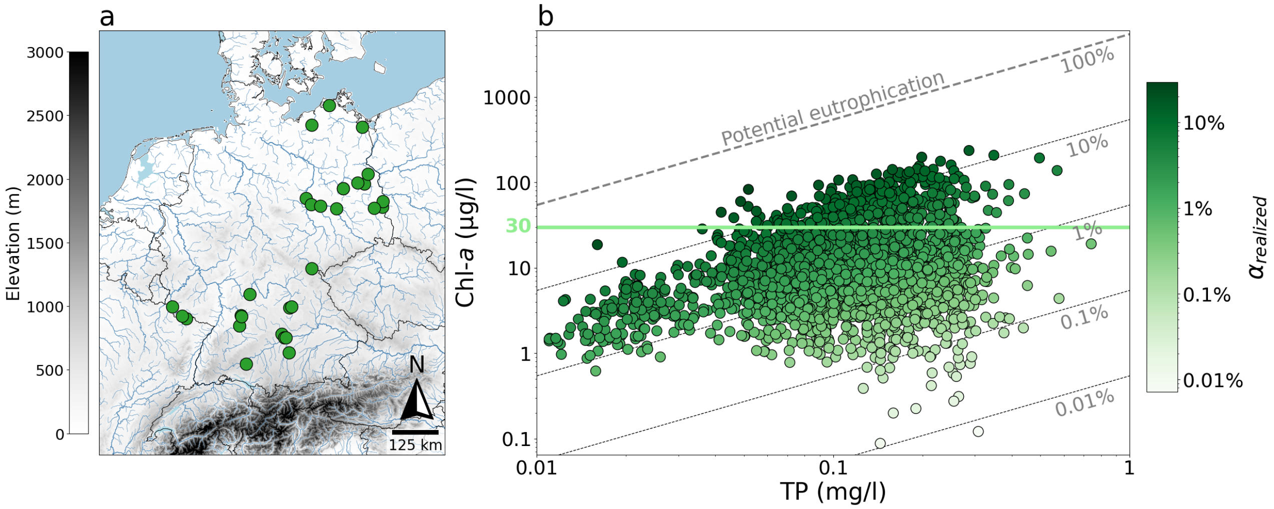

Figure 1. (a) Map of Germany showing the locations of the selected 30 river monitoring sites across Germany. (b) Scatter plot of 255×9 pairs of standardized TP and Chl-a concentration measurements from these stations. In the scatter plot, the degree of realized eutrophication, $\alpha_{realized}$, is indicated by colors and dashed lines. The green line shows the Chl-a threshold concentration of 30 µg/l for phytoplankton blooms (Dodds et al., 1998).

2.2 Degree of realized eutrophication

To link TP and Chl-a concentration data, we calculated the degree of realized eutrophication, $\alpha_{realized}$, according to Hubig et al. (2025):

$$\alpha_{realized} = \frac{\text{Chl-}a}{\text{Chl-}a_{potential}} \cdot 100\%. \tag{1}$$

This metric quantifies the realized, i.e., the measured Chl-a relative to a theoretical upper limit (Chl-$a_{potential}$) at a given TP level (Figure 1b), allowing to assess how efficiently river phytoplankton is using the available TP (Hubig et al., 2025). The upper maximum Chl-$a_{potential}$ is calculated as:

$$\text{Chl-}a_{potential} = \frac{\theta_{\text{Chl-}a}}{\theta_{\text{P},min}} \cdot \text{TP}. \tag{2}$$

Thereby, $\theta_{\text{Chl-}a}$ is the Chl-a content of phytoplankton expressed on a cellular carbon basis (g Chl-a g C^{-1}) and $\theta_{\text{P},min}$ the minimum P content of phytoplankton cells (g P g C^{-1}). The resulting $\alpha_{realized}$ is proportional to the measured Chl-a:TP ratio:

$$\alpha_{realized} = \frac{\theta_{\text{P},min}}{\theta_{\text{Chl-}a}} \cdot \frac{\text{Chl-}a}{\text{TP}} \cdot 100\%. \tag{3}$$

The used values $\theta_{\text{Chl-}a}$ = 0.03 g Chl-a g C^{-1} and $\theta_{\text{P},min} = 0.00552$ g P g C^{-1} as a median value for different phytoplankton species were taken from Hubig et al. (2025).

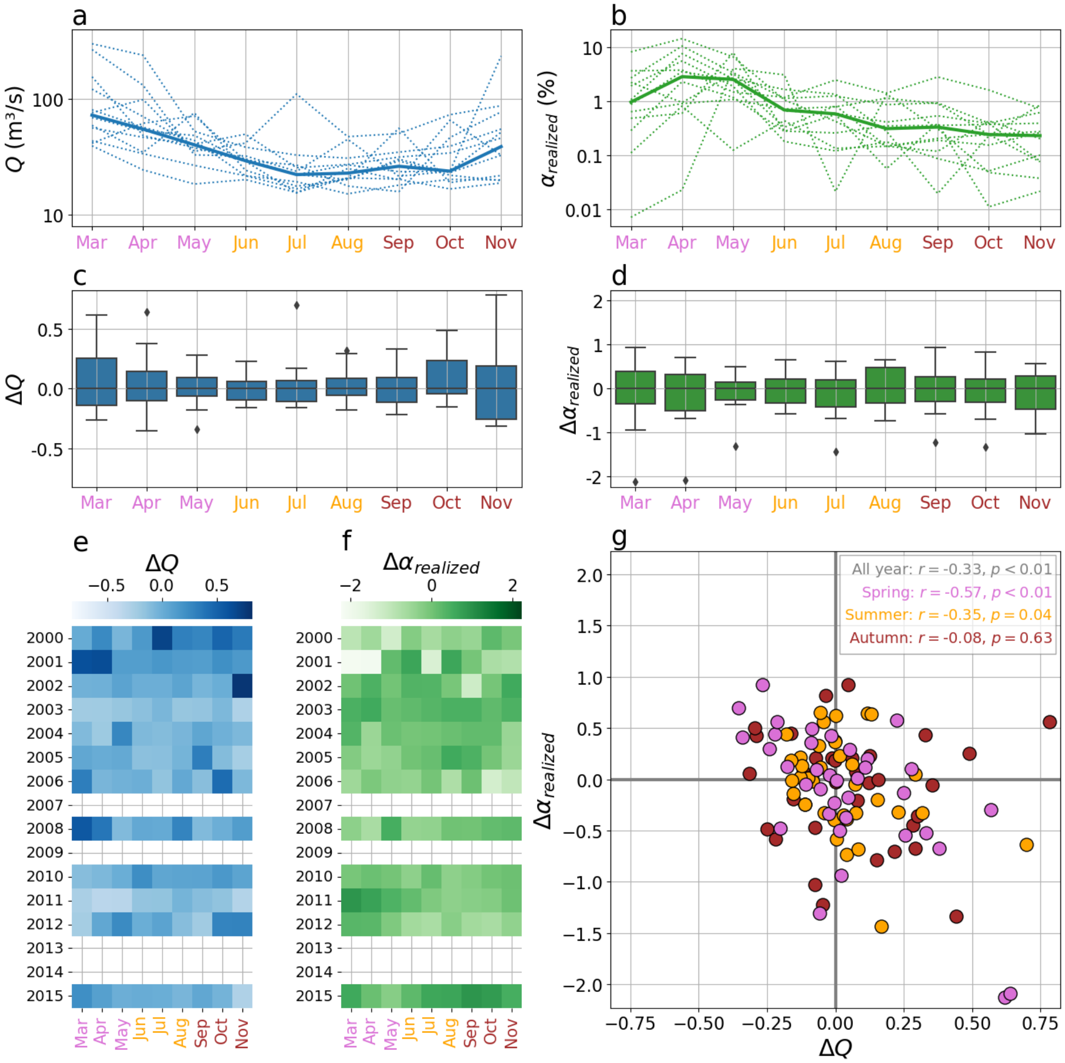

Figure 2. Procedure to derive Q and $\alpha_{realized}$ anomalies and their correlation for an example monitoring site at the Saar river. (a, b) From monthly data of the single years (dashed lines), median monthly data (solid lines) are subtracted to obtain (c, d) the anomalies ΔQ and $\Delta\alpha_{realized}$. (e, f) For all observation years at the example site, ΔQ and $\Delta\alpha_{realized}$ from March to November were obtained. (g) From ΔQ and $\Delta\alpha_{realized}$, Spearman rank correlation coefficients r based on all months and based on seasons (Spring, Summer, Autumn) were computed.

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2.3 Anomaly analysis

To investigate how interannual variations of Q affect $\alpha_{realized}$, we computed anomalies of Q and $\alpha_{realized}$ for each year and month at each station (Figure 2a-d). The anomalies ΔQ and $\Delta\alpha_{realized}$ were defined as

$$\Delta Q = log\left(\frac{Q}{Q_{median}}\right) = log(Q) - log(Q_{median}) \tag{4}$$

and

$$\Delta\alpha_{realized} = log\left(\frac{\alpha_{realized}}{\alpha_{realized,median}}\right) = log(\alpha_{realized}) - log(\alpha_{realized,median}), \tag{5}$$

where Q and $\alpha_{realized}$ represent the monthly discharge and degree of realized eutrophication in a given year, and Q_{median} and $\alpha_{realized,median}$ are the corresponding monthly medians across all years at the same station. At each station, monthly anomalies of ΔQ and $\Delta\alpha_{realized}$ were paired (Figure 2e-f) and Spearman rank correlations were computed (significance level $p = 0.05$) for all months combined, as well as per season, i.e., spring (March, April, May), summer (June, July, August), and autumn (September, October, November). This yields four correlation coefficients $r_{\Delta Q,\Delta\alpha_{realized}}$ per station (Figure 2g).

To further assess phytoplankton bloom risk under different hydrological conditions, we determined the bloom fraction, defined as the share of Chl-a measurements across all stations exceeding a bloom threshold of 30 $\mu g/l$ (Dodds et al., 1998, Figure 1b). To differentiate hydrological conditions, measurements were grouped into pronounced positive discharge anomalies ($\Delta Q > \Delta Q_{67}$), moderate discharge anomalies ($\Delta Q_{67} \geq \Delta Q \geq \Delta Q_{33}$), and pronounced negative discharge anomalies ($\Delta Q < \Delta Q_{33}$), with ΔQ_{67} and ΔQ_{33} being the 67- and 33-percentiles of ΔQ at a given site.

3 Results and Implications

3.1 Evidence of hydrologically controlled realized eutrophication

Our data indicate a consistent negative correlation of ΔQ with $\Delta\alpha_{realized}$, with anomalous low-discharge situations showing higher degrees of realized eutrophication (Figure 3a-d). Considering all months, the median correlation coefficient is $r_{\Delta Q,\Delta\alpha_{realized}} = -0.25$, with more than half of the 30 stations showing significant correlations (Figure 3a). This provides evidence that discharge deviations from the average are a key control on deviations in the efficiency of riverine phytoplankton to utilize available TP.

Correlations are more pronounced in spring than in summer or autumn, with a median $|r_{\Delta Q,\Delta\alpha_{realized}}|$ roughly twice as high and twice as many stations showing significance (Figure 3b-d). Yet, $\geq 20\%$ of stations exhibit significant negative correlations in summer and autumn, while positive correlations remain rare in all seasons. We note that seasonal coefficients are based on only three data points per year (at least 15 per station) versus nine for annual correlations (at least 45 per station), reducing their statistical power.

We argue that weaker correlations in summer and autumn likely reflect more complex phytoplankton controls compared to in spring. Many rivers show $\alpha_{realized}$ spring peaks followed by summer declines, potentially driven by intensified benthic

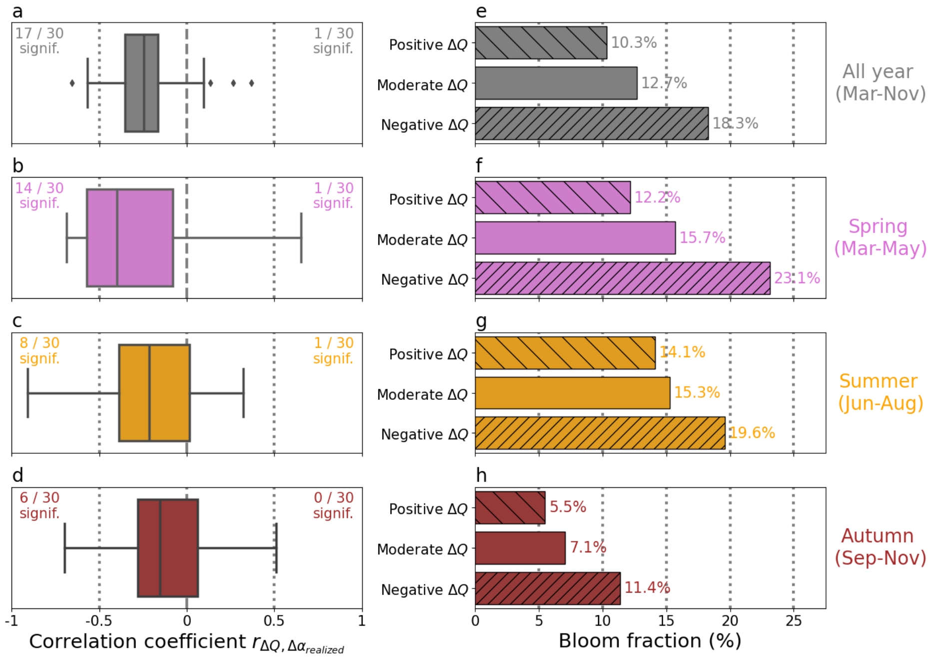

Figure 3. (a-d) Spearman rank correlation coefficients $r_{\Delta Q, \Delta\alpha_{realized}}$ for all individual 30 stations. (e-h) Bloom fractions (share of Chl-a concentrations > 30 µg/l across stations) for pronounced positive ($\Delta Q > \Delta Q_{67}$), moderate ($\Delta Q_{67} \geq \Delta Q \geq \Delta Q_{33}$), and pronounced negative ($\Delta Q < \Delta Q_{33}$) discharge anomalies. ΔQ_{67} and ΔQ_{33} are the 67- and 33-percentiles of ΔQ at a given site. Both r and bloom fractions were separately determined for (a+e) all covered months and for (b+f) spring, (c+g) summer, and (d+h) autumn. In panels (a-d), the numbers of significant negative (upper left) and positive correlations (upper right) are shown relative to the total number of stations (significance level $p = 0.05$).

grazing, increased riparian shading from leaf cover, or slower-growing phytoplankton species (Hubig et al., 2026). Longer residence times during low discharge favor the efficiency of grazers (e.g., Pigneur et al., 2014), possibly counteracting its stimulating effects on phytoplankton growth and thus weakening the Q-$\alpha_{realized}$ relationship in summer and autumn.

While not well represented in our $2000-2019$ dataset, unprecedented summer blooms in recent hot and dry years since 2017 (Kleinteich et al., 2024; Köhler et al., 2024) suggest that the summer Q-$\alpha_{realized}$ relationship may strengthen under future warmer and drier conditions. Potential causes include an increasing dominance of high-temperature-adapted cyanobacteria (Paerl and Otten, 2013; Kleinteich et al., 2024) and other phytoplankton species potentially less palatable to grazers (Köhler et al., 2024), alongside potential grazing declines above critical temperature thresholds (Lei et al., 1996). Our observed discharge-phytoplankton link may thus be underestimated under extreme drought conditions.

3.2 Increased risk of phytoplankton blooms under anomalous low-discharge conditions

Beyond indicating a mechanistic link between interannual discharge variability and the degree of realized eutrophication, our results show that phytoplankton blooms (i.e., Chl-a concentration > 30 $\mu\mathrm{g/l}$) occur more frequently with negative discharge anomalies than with positive anomalies (Figure 3e-h). Across stations and months, the bloom fraction is 1.4-fold higher for pronounced negative ΔQ than for moderate ΔQ and 1.8-fold higher than for pronounced positive ΔQ (Figure 3e). We note that some stations are most of the time above the bloom-threshold, thus their exceedance risk is independent of discharge anomalies (Hubig et al., 2025).

Seasonally, the largest absolute difference between negative and positive discharge anomalies occurs in spring, where the bloom fraction reaches 23.1% for pronounced negative anomalies (Figure 3f), 1.5-fold higher than for moderate anomalies and 1.9-fold higher than for pronounced positive anomalies. In summer, the absolute differences (4.6% and 5.5%) and the ratios (1.3 and 1.4) are less pronounced (Figure 3g). Although the bloom fraction in autumn is generally lower than in spring and summer, the ratio between pronounced negative and positive discharge anomalies is highest, reaching 2.1 (Figure 3h).

The absolute Chl-a concentrations and bloom fractions are primarily controlled by nutrient availability (TP concentrations) and spatial and seasonal patterns of $\alpha_{realized}$ (Hubig et al., 2025, Hubig et al.; 2026). However, our results demonstrate that locally, discharge deviation from the average behavior can be crucial in determining whether blooms develop.

4 Conclusions

By analyzing a multi-year dataset of Q, TP, and Chl-a measurements from 30 monitoring sites across Germany, we found evidence that deviations from average discharge conditions influence the degree of realized eutrophication, i.e., the level of phytoplankton biomass at a given TP concentration. Specifically, lower-than-average discharge at a site is associated with a higher degree of realized eutrophication, and vice versa. We further found that phytoplankton blooms occurred about 1.8 times more often under pronounced negative discharge anomalies (below the 33-percentile) than under pronounced positive anomalies (above the 67-percentile). This indicates that discharge anomalies can play a crucial role in determining whether phytoplankton blooms develop.

Under projected longer and more intense drought conditions with stronger negative discharge anomalies (Rakovec et al., 2022), higher $\alpha_{realized}$ implies that given TP concentrations will translate into increased Chl-a levels (Figure 1b). Consequently, if TP inputs remain unchanged, phytoplankton blooms are expected to become more frequent, thus counteracting efforts to reduce nutrient pollution and shrinking our save operation space for riverine nutrient management. Consequently, eutrophication management strategies focused on reducing nutrient concentrations may need to adopt stricter nutrient thresholds to effectively prevent future elevated phytoplankton biomass and algal blooms.

Data availability. The observational water quality data are largely part of the QUADICA database (Ebeling et al., 2022, 2026). All original water quality data were provided by German environmental authorities, including for stations not included in QUADICA. For details, refer to Hubig et al. (2025).

Author contributions. AH prepared the manuscript; PE and AM provided feedback.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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