

Author's response

egusphere-2025-656

Dear Editor and Reviewers,

Thank you very much for your valuable comments. The point-by-point responses to your comments are listed below.

Report #1

The authors did incorporate and build upon my initial comments and thoughts. I especially enjoy reading the new discussions on atmospheric exchange and nutrient limitation. Also, the additional information in the supplement is now sufficient to understand the modeling.

Still, I would heavily suggest that the authors revise Fig. 2 and 3 by adding a legend that explains what the blue and red lines represent (this would make it easier for a reader who skipped the text). Only Fig. 2 explains the red line.

Response: Thank you for the acknowledgement of our responses to the review in the last round. Regarding the suggestion of Fig. 2 and 3, we now added a legend that explains what blue and red lines represent. Thanks for the suggestion.

Report #2

The study demonstrates that the extreme low-flow conditions of summer 2018 in the Lower Bode stream led to marked alterations in some water quality and ecosystem functioning parameters. Elevated water temperature and chlorophyll-a concentrations coincided with reduced dissolved oxygen and nitrate levels. Stronger diurnal oxygen fluctuations and a significant increase in gross primary productivity, dominated by benthic algae, were observed alongside higher ecosystem respiration, resulting in near-zero net ecosystem productivity. Although less clear, net nitrate uptake rates did not change, the proportion of nitrate removed increased significantly due to benthic algae assimilation, indicating a more efficient internal nutrient cycle during extreme drought conditions.

The manuscript provides novel insights by employing high-frequency, reach-scale measurements to assess ecosystem responses under extreme low flow, a methodological approach still rare in the literature compared with studies based on traditional grab sampling schemes. This study adds to a growing body of recent research of drought effects on aquatic hydrology, ecology and biogeochemistry by providing novel insights into water quality and instream ecosystem processes under extreme low-flow conditions. It is both original and significant, as it enhances our understanding and predictive capacity regarding the

consequences of more frequent and severe droughts in Central Europe under climate change, with clear implications for freshwater ecosystem management.

Overall the ms. is very clearly presented, well-structured and relies on highly valuable, high quality data.

Response: Thank you for the nice summary of the manuscript.

Major comments

- The relative simplicity of the comparative analysis between drought and extreme summer drought conditions makes the results easy to follow and convincing. However, I believe that a Q-C and/or hysteresis-type analysis could help to better understand the sensitivity of each site, water quality parameter or ecosystem process to changing flow conditions, as well as the trajectory of these responses during flow reduction (in a drought) and flow recovery (after the drought).

Response: Thank you for the valuable comment. As the reviewer noted, our comparative design was intended to provide clear and direct evidence of the impact of extreme summer low flow on water quality. We agree that C–Q and hysteresis analyses are powerful tools for quantifying site sensitivity and for examining the trajectories of water quality responses during drought onset and recovery. While our dataset would allow such analyses, this study focuses specifically on a direct comparative framework to highlight the effects of extreme low-flow conditions in a straightforward and convincing manner. A full C–Q or hysteresis-based investigation would require a different analytical design and is therefore beyond the scope of the present paper.

In recognition of the relevance of this suggestion, we have elaborated Section 3.7 to emphasize this as an important direction for future work as follows: Moreover, future research is encouraged to leverage high-frequency datasets and apply C–Q and hysteresis approaches to assess short-term nutrients and ecosystem dynamics and to investigate the underlying mechanisms during both drought onset and recovery, thereby extending the insights gained from our comparative analysis.

- One of the paper's most innovative goals is to exploit cutting-edge sensor technologies to more effectively capture the rapid and novel mechanisms underlying water quality and ecosystem functioning responses under low-flow conditions. However, one of the major challenges is to properly calibrate these sensors. While this issue has already been resolved for some parameters included in the study, for others it remains quite complex and requires a solid set of 'classical measurements' taken in the field and covering environmental gradient comparable to those of the study. Although the paper does mention this aspect, it lacks a detailed description of the protocols followed to calibrate the *Chl-a* and NO_3^- sensor-based measurements with classical sampling and laboratory analyses.

Response: Thank you for this helpful comment. Both sensors were routinely calibrated on a monthly basis as part of our maintenance program. For NO_3^- , we compared sensor readings with laboratory-analyzed grab samples and applied corrections following the established methodology of Rode et al. (2016) from the Bode observatory in the Selke River. In that study, the method achieved an R^2 of 0.93 with low bias at Station Meisdorf. In our case, we also provide a comparison of sensor and laboratory measurements, together with the corrected NO_3^- data for the GGL station in the Supplement (Fig. S5), which demonstrates the good agreement between the original sensor measurements and the grab samples, with only minor bias.

Sensor data were corrected against grab samples using our automated MATLAB data-cleaning tool, which shifts the continuous sensor signal to align with laboratory results when necessary. This step is particularly important for NO_3^- because of the characteristics of the UV-Vis absorbance method: the optical path length is fixed during measurements, while the optimal path length depends on concentration (e.g., ~ 1 cm for low concentrations and ~ 0.2 cm for high concentrations). When concentrations vary strongly, measurement uncertainties may occur if the path length remains constant. Corrections against laboratory data are therefore especially relevant during rare periods of elevated NO_3^- concentrations. We apply this correction only to nitrate for the above methodological reason, and an example of this adjustment is shown in Fig. S5 for the GGL Station.

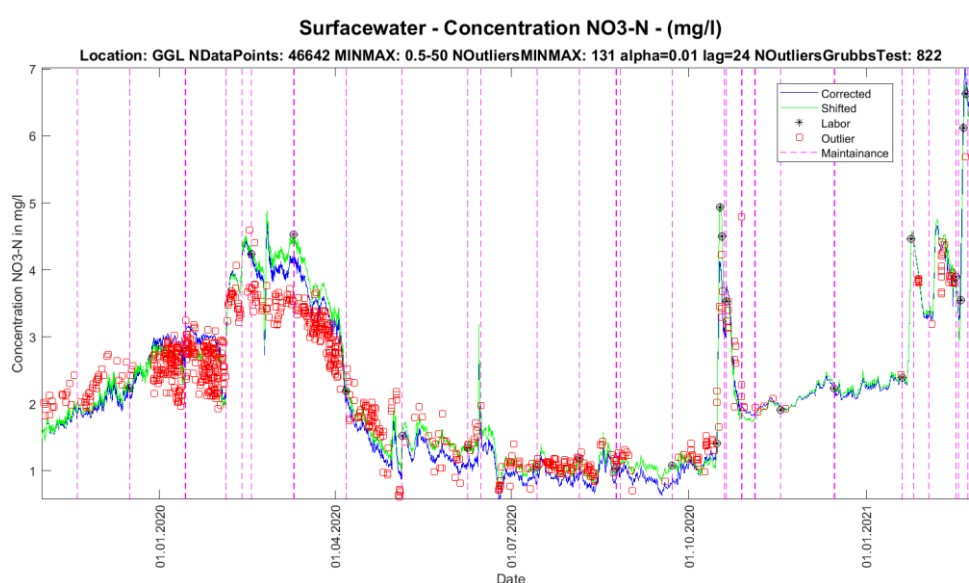


Fig. S5 Comparison of nitrate (NO_3^- -N) concentrations measured by sensor and laboratory analyses, including data adjustments at the GGL station.

For *Chl-a*, sensor measurements and laboratory grab samples collected at STF between 2011 and 2019 showed very good agreement, with an R^2 of 0.85 (also provided in SI as Fig. S6).

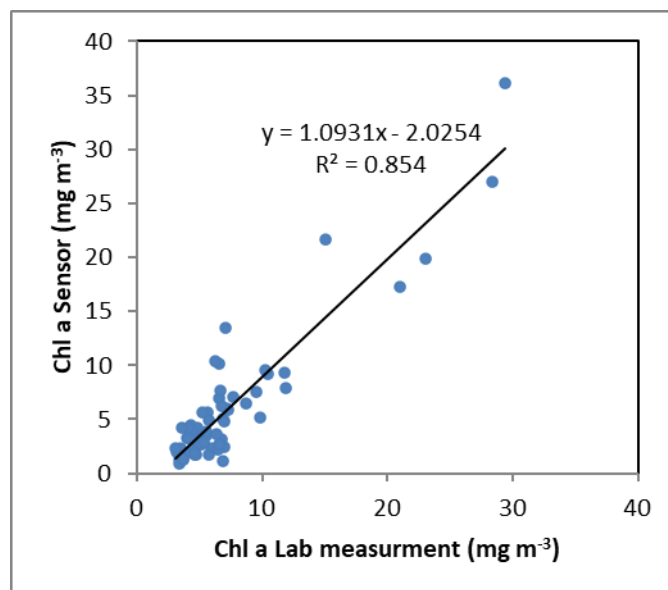


Fig. S6 Relationship between *Chl-a* concentrations measured by sensors and laboratory grab samples at the STF station from 2011 to 2019.

In the revised manuscript, additional text has been included in Section 2.3 to address this point.

- The manuscript provides a description of in-stream aerobic metabolism modeling, but the presentation lacks sufficient detail on key aspects of the model and the results obtained. Uncertainties in the estimates are mentioned, yet the sources of variability and how they influence the results are not fully explored. While the potential integration of lateral oxygen inflows is briefly discussed, the evaluation remains superficial and does not convincingly demonstrate their impact. Alongside the previous, some examples of observed versus modeled dissolved oxygen concentrations should be included in the supplementary information.

Response: Thank you for the comment. In this study, we applied the single-station method, which relies on high-frequency dissolved oxygen (DO) time series. In this approach, DO is measured directly by sensors and not modeled as an output; instead, the measured DO serves as the basis for estimating ecosystem metabolic rates. Therefore, no direct comparison between modeled and observed DO concentrations is available within this study. However, in our previous work (Huang et al., 2022), DO was modeled using the WASP framework for the same reach and study period. Comparisons of modeled and observed DO concentrations for the full 5-year period and the ExLF phase can be found in Figures 2(e) and S5 of that publication.

Minor comments

- Lines 96-101*: This level of detail, including the description of the statistical tests used, is not meant to be included in the introduction.

Response: Thank you for the comment. We have deleted the details of statistical tests used in the revised manuscript.

- Line 243: Panel letters of Figure 3 are missing in the Figure but referenced in the text.

Response: Thank you for the comment. The panel letters of Figure 3 are added in the revised manuscript.

- Line 293: Correct: “at GGL by 0.45 mg L⁻¹ at GGL ($p < 0.01$) and non-significantly at STF 0.28 mg L⁻¹”:

Response: Thank you for the comment. We have corrected the text in the revised manuscript.

- Line 295: add by between “and” and “0.73”.

Response: Thank you for the comment. We have added it to the revised manuscript.

- Line 370: remove mobile

Response: Thank you for the comment. We have removed it from the revised manuscript.

- Line 377: expand the how in-stream processes can affect/are affecting NO₃⁻ removal. What about other dissolved inorganic N forms.

Response: Thank you for the valuable comment. Now we have expanded the discussion of instream processes affecting nitrate removal in Section 3.4 as below.

Beyond reduced lateral NO₃⁻ loading, enhanced instream processing could have further amplified spatial heterogeneity between upstream and downstream. Nitrate dynamics in streams are governed by three main instream processes: assimilation, denitrification (the only permanent removal pathway), and regeneration through nitrification. Under ExLF conditions, water residence time in the reach increased by 45% (Table 1), and reaction rates were enhanced by 7.1% at STF due to higher temperatures (based on a simplified Arrhenius calculation, Section 3.1). Although mean NO₃⁻ concentrations decreased by 9.5% at STF (Table 1), these hydrological and thermal changes likely enhanced denitrification and overall NO₃⁻ removal. Furthermore, as discussed in Section 3.6, the significant 46% increase in areal GPP during ExLF suggests that gross NO₃⁻ uptake rates also increased. Nitrification is likewise expected to intensify under longer residence time and elevated temperature, potentially increasing NO₃⁻ production. Indeed, NH₄⁺ concentrations were higher during ExLF than LF (Fig. S1 in Huang et al. (2022)), further supporting higher NO₃⁻ production via nitrification. However, our NH₄⁺ dataset is limited to monthly sampling, which prevents a robust quantification of this process. Notably, elevated NH₄⁺ concentrations have also been reported in northern boreal streams during the 2018 drought (Gómez-Gener et al., 2020). Among these pathways, gross NO₃⁻ uptake appears to be the dominant driver. Long-term model estimates for this reach indicate a mean gross NO₃⁻ uptake rate is 60.5 mg N m⁻² d⁻¹, compared with a mean denitrification rate of 14.1 mg N m⁻² d⁻¹ (Table S3 in Huang et al. (2022)). Thus, enhanced assimilatory uptake under ExLF likely played a decisive role in net NO₃⁻ removal. Although nitrification may also have increased, NH₄⁺ concentrations remained below 0.1 mg N L⁻¹—far lower than NO₃⁻ concentrations—suggesting that the magnitude of nitrate regenerated was smaller than the combined removal via uptake and denitrification. Overall, this balance

indicates that the increases in sink processes exceeded source processes during ExLF, which likely contributed to the greater upstream–downstream disparity in NO_3^- concentrations. This pattern aligns with findings by Hensley et al. (2019) and is consistent with broader evidence for reductions in NO_3^- concentrations during droughts in streams and rivers through diminished catchment inputs and enhanced in-stream retention (Caruso, 2001; Dupas et al., 2025; Mosley et al., 2012; Muchmore and Dziegielewski, 1983).

- The following key references on this topic are missing (Gómez-Gener et al. 2020; Dupas et al. 2025; Harjung):

Dupas, R., A. Lintern, A. Musolff, C. Winter, O. Fovet, and P. Durand. 2025. Water quality responses to hydrological droughts can be predicted from long-term concentration–discharge relationships. *Environ. Res.: Water* **1**: 015001. doi:10.1088/3033-4942/adb906

Gómez-Gener, L., A. Lupon, H. Laudon, and R. A. Sponseller. 2020. Drought alters the biogeochemistry of boreal stream networks. *Nat Commun* **11**: 1795. doi:10.1038/s41467-020-15496-2

Harjung, A. Impact of drought periods on carbon processing across surface-hyporheic interfaces in fluvial systems. 232.

Response: Thank you for mentioning the key references. They are very helpful. Now we have cited the first 2 references in the revised manuscript in Section 3.4 and 3.3.

References

Rode, M., Halbedel née Angelstein, S., Anis, M. R., Borchardt, D., and Weitere, M.: Continuous In-Stream Assimilatory Nitrate Uptake from High-Frequency Sensor Measurements, *Environmental Science & Technology*, 50, 5685-5694, 10.1021/acs.est.6b00943, 2016.

Huang, J., Borchardt, D., and Rode, M.: How do inorganic nitrogen processing pathways change quantitatively at daily, seasonal, and multiannual scales in a large agricultural stream?, *Hydrol. Earth Syst. Sci.*, 26, 5817-5833, 10.5194/hess-26-5817-2022, 2022.