

Dear Referee,

we thank you for your time in reviewing our manuscript and your constructive feedback. We see feasible implementing all your suggestions in a revised version of the manuscript. In particular, we have now assessed long-term variations in additional streamflow metrics and carefully evaluated our approach for the estimation of the dynamic storage of the catchments. We plan to introduce these additional analyses in a revised version of the manuscript. We also intend discussing more the reasons for our methodological choices and potential uncertainties in the study.

Please find below our point-by-point reply to your comments (italic) and the changes we propose to do in the manuscript to address them (underlined).

Best regards,

Giulia Bruno and co-authors

Bruno et al. analyzed the decreasing trend of low flow in 363 small catchments in Germany. They also attributed the decrease to the increase of ET. They further unraveled that the change of P-Q relationship during drought produces lower flow which is generally due to the increased ET. They conducted this work based on observations of P and Q, empirical expression of subsurface storage, and ET derived based on water balance and statistical analysis. I think studying the decrease of low flow and trying to find the major drivers is very important in the climate change background. The data and analysis are generally reliable, the structure and the writing are good. However, there the following concerns which need clarification from authors for further review.

We thank you for your overall positive evaluation of our manuscript and for raising interesting points to improve our work.

- 1. I was more or less confused by the overall idea of the authors. If you wanted to check if the decrease of the flow is caused by increased ET, and you also have calculated the water balance, why not do a straightforward analysis of the overall change of P, ET, Q, and S. Then it is easy to get if the decrease of flow is mainly driven by ET. Then you can do the analysis in your manuscript as a follow-up. Otherwise, I feel the conclusions are even not that convincing as, for example, the decrease of low flow might be just because of the shift of the timing of streamflow.*

We understand that you suggest evaluating here the impact of changes in catchment evapotranspiration (E) on streamflow (Q) at an annual time scale. This has already been well documented for several regions and periods, partly overlapping with our case study as well (Teuling et al., 2009; Fischer et al., 2023; Renner & Hauffe, 2024). Here, we rather aimed at assessing the impact of increases in E on Q during dry periods specifically, to complement these previous findings. We see, however, that assessing changes in additional Q metrics, such as annual Q and its timing, may provide useful context regarding hydrological changes in the region and the decreases in the magnitude of summer low flows that we observed. Therefore, we have now quantified changes in annual Q and its timing, the latter through the center of mass date of Q (CMD_Q , Court, 1962; Han et al., 2024). Annual Q and CMD_Q generally showed decreases across the catchments between 1970 and 2019 (Fig. 1 and 2 here). However, these decreases were less significant than those in the magnitude of summer low flows, with a median trend in annual Q (CMD_Q) of $-1.3 \text{ \% decade}^{-1}$ ($-0.006 \text{ month year}^{-1}$) across all catchments and significant negative trends in 10 (3) % of them, as compared to a median trend in

$7dQ_{\min, JJA}$ of $-3.7 \text{ \% decade}^{-1}$ across all catchments and significant negative trends in 31 % (see Fig. 1 and 2 here for annual Q and CMD_Q , and Fig. 4 in the manuscript for $7dQ_{\min, JJA}$).

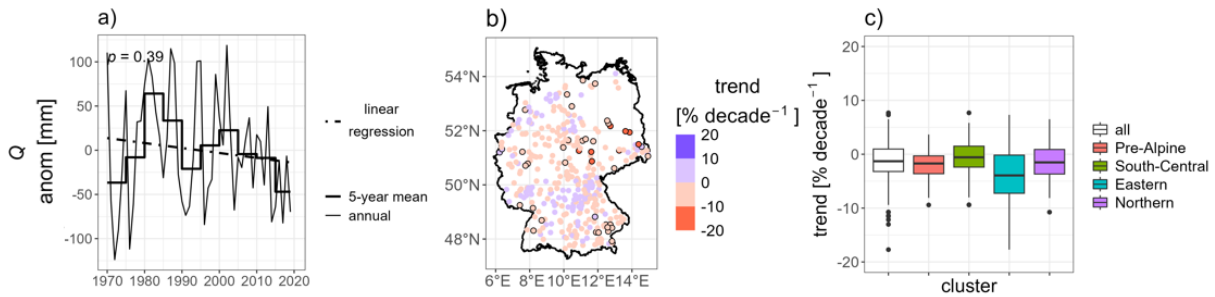


Fig. 1: Long-term variations in annual streamflow (Q) over 1970–2019. (a) Average anomalies across the study catchments. (b) Map of catchment-scale trends (black edges if significant). (c) Boxplots of trends for all catchments and by cluster.

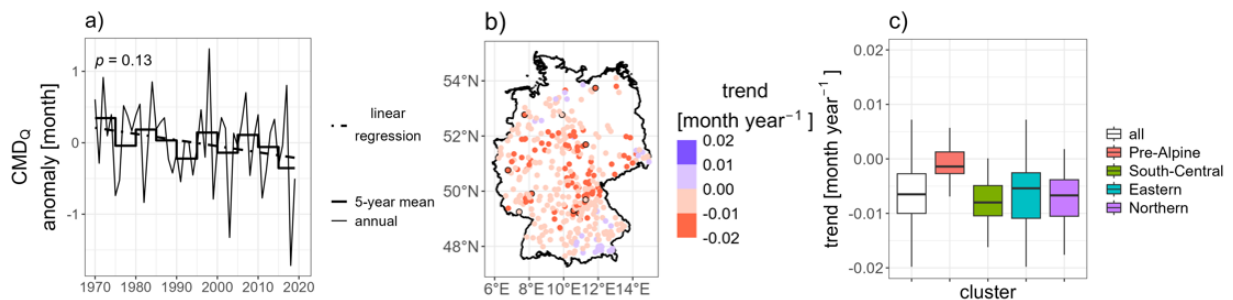


Fig. 2: Long-term variations in the centre of mass date of streamflow (CMD_Q) over 1970–2019. (a) Average anomalies across the study catchments. (b) Map of catchment-scale trends (black edges if significant). (c) Boxplots of trends for all catchments and by cluster.

Therefore, summer low flows in particular decreased across the study catchments between 1970 and 2019, as compared to other Q metrics, and these decreases did not occur simply with an overall decrease in Q or a shift in its timing. We plan to introduce this analysis in a revised version of the manuscript, by adding Fig. 1 and 2 in the Supplement, and methodological aspects, results, and discussion of this new analysis in the corresponding sections.

Methods: To characterize general long-term variations in Q , we also considered annual Q and the center of mass date of Q (CMD_Q). CMD_Q is the time of the year in which half of the annual Q occurs and as such, a metric for Q timing (Court, 1962; Han et al., 2024).

Results: Additional Q metrics similarly decreased over 1970–2019, even though less significantly than summer low flows (median trend in annual Q of $-1.3 \text{ \% decade}^{-1}$ across all the catchments and significant negative trends in 10 % of them, and median trend in CMD_Q of $-0.006 \text{ month year}^{-1}$ across all the catchments and significant negative trends in 3 % of them).

Discussion: Furthermore, decreases in annual Q and in its timing (CMD_Q) were more elusive than those in summer low flows, meaning that summer low flows in particular decreased across the study catchments over 1970–2019, and likely not simply due to a general decrease in Q or a shift in its timing.

Furthermore, we intend adding more context around current knowledge on the effect of increases in E on decreases in Q at an annual time scale in the Introduction and Discussion as follows, also to highlight better the novelty of our study with respect to previous literature.

Introduction: Furthermore, increases in E contributed to decreases in annual Q on the long-term (Teuling et al., 2009; Fischer et al., 2023; Renner & Hauffe, 2024) and during dry years (Tran et al., 2023), especially in mountain catchments.

Discussion: Our findings on the role of increases in E on decreases in summer low flows expand results at annual time scale (Fischer et al., 2023; Tran et al., 2023), and those by Montanari et al. (2023) on concomitant decreases in summer low flows and increases in E in northern Italy over recent decades.

2. *You mentioned you used Kirchner's approach to calculate S_{dyn} which needs that S is the main control of Q generation. I am wondering if the 363 catchments you used meet this requirement and where is your analysis for this?*

We agree that the assumption of Q mainly controlled by the dynamic storage (S_{dyn}) may not always hold true across large samples of catchments, despite previous studies adopted it (Staudinger et al., 2017; Trotter et al., 2024) also in our study region (Stoelzle et al., 2013; Berghuijs et al., 2016). We have now evaluated this assumption similarly to what done by Kirchner (2009). Specifically, we computed the percentage of winter days (November to April, included) with (i) rising Q ($dQ/dt > 0$) when precipitation (P) exceeds Q , and (ii) decreasing Q ($dQ/dt \leq 0$) when P does not exceed Q . This can be thought as the percentage of days when S_{dyn} is the main control of Q , with S_{dyn} replenishing when P exceeds Q (condition i) and depleting otherwise, with no additional main sources of sustainment for Q (conditions ii). We found that all catchments met these conditions for most of the days over the study period (Fig. 3 here). The percentage of days with S_{dyn} as main control of Q spanned indeed between 54 and 72% across the catchments. This therefore shows the suitability of the method that we used for the estimation of S_{dyn} for our case study. We propose to add this analysis to a revised version of the manuscript, by rephrasing L144–146 as follows.

Kirchner (2009) showed that S_{dyn} can be derived from Q time series and the recession characteristics of the catchments, under the assumption of Q mainly controlled by it. To verify this assumption for the study catchments, we followed an approach similar to Kirchner (2009). Specifically, we computed the percentage of winter days (November to April, included) over the study period with (i) rising Q ($dQ/dt > 0$) when P exceeds Q and (ii) decreasing Q ($dQ/dt \leq 0$) otherwise. These conditions indicate limited influence of additional stores which are fed during P events and then sustain Q during dry periods. The percentages of days for which S_{dyn} can be thought as the main source of Q spanned between 54 and 72% across the catchments, meaning that the assumption underlying the method proposed by Kirchner (2009) is met for most of the time in all catchments.

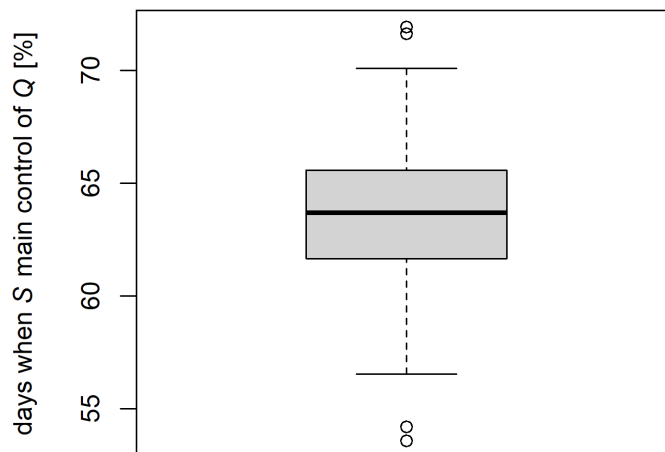


Fig. 3: Distribution of the percentage of days when storage (S) is the main control of streamflow (Q), across all catchments.

3. *So, how do you quantify the uncertainties in E you derived from water balance as I am not sure the uncertainties in S_{dyn} .*

Deriving E through a water balance approach may involve considerable uncertainties from the assumptions around potential changes in catchment storage (S) and data themselves (see reply to comment #1 by Referee #1). Bruno & Duethmann (2024) extensively studied uncertainties in long-term variations in water balance-derived E for small catchments without substantial water management in Germany, by using the same approach and datasets as here. This work revealed that the main source of uncertainty is P rather than assumptions regarding S and long-term variations in S_{dyn} largely agreed with those from groundwater data. Bruno & Duethmann (2024) furthermore showed that long-term variations in E were generally robust in the study region with respect to alternative data sources. We realize that we currently do not discuss potential uncertainties in E in light of Bruno & Duethmann (2024). We propose to refer to this work in the Introduction already, by rephrasing L72–73 as follows, and to discuss it in a new section on uncertainties in this study (4.4 Sources of uncertainty).

L72–73: Bruno & Duethmann (2024) reported robust increases in E in small catchments in Germany between the 1970s and 2000s, regardless of uncertainties in P data and in the consideration of potential S changes.

4.4 Sources of uncertainty: Bruno and Duethmann (2024) moreover showed that long-term variations of water balance-derived E were generally robust to uncertainties in P and S for small catchments in Germany over the last five decades, and coherent with those from point-scale E data.

4. *Also, I have to say, for the catchments with areas ranging from 50-150km², the lateral groundwater flow is significant which has been discussed in Ying Fan's paper 'Are catchments leaky?' and also quantified in our research (not published yet). Therefore, Equation 3 might be problematic.*

We agree that estimating E from P and Q observations implies considerable uncertainties for some catchments (Fan, 2019; Kampf et al., 2020; Safeeq et al., 2020). However, here we are mostly interested in long-term variations in E at a regional scale. For this, we argue that alternative approaches can be equally challenging, given issues in modelling long-term variations in E (Duethmann et al., 2020) and in the representativeness of satellite-derived products for small catchments. Thus, we chose this approach, in line with several previous works (e.g., Teuling et al., 2009; Ukkola et al., 2013; Duethmann and Bloeschl, 2018; Bruno and Duethmann, 2024). Bruno and Duethmann (2024) furthermore compared trends in water balance-derived E and in E data from lysimeters and flux towers in Central Europe. Despite the general paucity of point-scale data, these showed similar temporal dynamics to water balance-derived E . This reinforces the suitability of the water balance-approach to study long-term variations in E in our study region. We acknowledge, however, that E estimates may be still uncertain for individual catchments and years, due to potential data issues and intercatchment groundwater flows. To tackle these uncertainties, we therefore performed the multiple linear regressions on cluster-, 5-year averages. To provide more context around our methodological choices, the associated uncertainties, and our strategies to minimize them, we plan to rephrase L167–169 and to add more discussion in the new Section 4.4 as follows.

L167–169: We adopted 5-year averages to focus on long-term dynamics and reduce potential uncertainties in water balance-derived E . Moreover, for the cluster-scale analysis we used average time series across the catchments in each cluster to minimize uncertainties in E for specific catchments, while analysing the main signal at a regional scale.

4.4 Sources of uncertainty: Due to the generally coarse resolution of satellite-derived E estimates, we computed E from observed P and Q , and estimates of the S_{dyn} of the catchments from Q data as a first order approximation of S . This approach may be problematic for specific catchments, such as those with relevant intercatchment groundwater flows (Fan, 2019; Kampf et al., 2020; Safeeq et al., 2021). Yet, previous works often used a water balance-approach to study long-term variations in E (Teuling et al., 2009; Ukkola and Prentice, 2013; Duethmann and Blöschl, 2018; Bruno and Duethmann 2024). Bruno and Duethmann (2024) moreover showed that long-term variations of water balance-derived E were generally robust to uncertainties in P and S for small catchments in Germany over the last five decades, and coherent with those from point-scale E data. Here, we further aimed at minimizing uncertainties in E for specific catchments and years by using cluster-, 5-year averages in the multiple linear regressions for trend attribution (Section 2.5).

5. *Line 161, P_{DJF} and P_{MAM} are used as proxies of storage processes. How and why they are used as proxies?*

Long-term data on soil moisture and groundwater storage are unavailable for the large number of small catchments that we analyze here. Thus, we used precipitation over winter (P_{DJF}) and spring (P_{MAM}) as proxies for storage recharge in the seasons preceding the dry period in the study region, as frequently done (Duethmann et al., 2015; Saft et al., 2016; Laaha et al., 2017). Following comment #2 by Referee #1 too, we propose to rephrase L161–162 as follows and to add more discussion on this point in the new Section 4.4.

L161–162: Since long-term data on soil moisture and groundwater storage are not available for the study catchments, we used P_{MAM} and P_{DJF} as proxies of storage recharge in the seasons preceding the dry one (Duethmann et al., 2015; Saft et al., 2016; Laaha et al., 2017).

4.4 Sources of uncertainty: Finally, as potential predictors of changes in summer low flows we approximated storage processes with P in the season preceding the dry one, due to unavailability of long-term S data for the study catchments. We chose this approach instead of using alternative proxies for S (e.g., estimates of S_{dyn} or baseflow from Q data) to avoid dependences between predictors and target variable (summer low flows). The satisfactory performances of the multiple linear regressions and the plausible signs of their coefficients suggest the suitability of the selected predictors to represent the long-term dynamic of summer low flows (Table S1).

6. *All conclusions occur in less than 30% of the catchments, so how do you think about the generality of the study?*

The main findings of this study can be summarized as:

- The magnitude of summer low flows consistently decreased across 363 small catchments with no substantial water management in Germany over 1970–2019 (Fig. 4 in the manuscript);
- Increases in E were a relevant driver of these decreases, especially for catchments in the Eastern area (Fig. 6 and 7);
- Changes in the P - Q relationship occurred in catchments with underlying increases in E during a multi-year drought between 1989 and 1993 (Fig. 8).

With respect to first finding, most of the catchments experienced a tendency to decreases in summer low flows, with negative trends in 77% of the catchments and an interquartile range of $-7.5/-0.6$ % decade⁻¹ (white boxplot in Fig. 4c). Furthermore, significant negative trends occurred in 31% of the catchments, while significant positive trends in the 2% only (Fig. 4b). To better highlight the general

decreasing tendency in summer low flows across the catchments, we propose to complement L15 and L212–213 as follows.

L15: Summer low flows decreased (increased) significantly in 31 % (2 %) of the catchments, with a median trend of -3.7 % decade⁻¹ across all catchments.

L212–213: Trends in $7dQ_{\min, JJA}$ were significantly negative in 31 % of the catchments and significantly positive in 2 % of them (negative in 77 % and positive in 23 %, Fig. 4b), with median (interquartile range, IQR) of -3.7 (-7.5/-0.6) % decade⁻¹ across all catchments (Fig. 4c).

Regarding the relevance of increases in E for decreases in summer low flows (second finding) and for changes in the P - Q relationship during multi-year droughts (third finding), we acknowledge that additional processes were also important for decreases in summer low flows in specific clusters (Fig. 6 and 7 in the manuscript) and hydrological changes occurred rather sparsely during the multi-year drought under study (see also reply to the comment #5 by Referee #1). However, we believe that our findings are relevant well beyond our study region, given the strong increases in E in many regions worldwide in recent decades (Teuling et al., 2009; Ukkola & Prentice, 2013; Duethmann & Blöschl, 2018; Yang et al., 2023) and their generally limited consideration in low-flow and drought analyses. We plan to highlight better the relevance of our findings outside our study region in a revised version of the manuscript, by adding a paragraph in the Discussion, and rephrasing L396–397 and L410–411 as follows.

Discussion: However, attributing decreases in summer low flows to their causes is still challenging (Montanari et al., 2023) and similarly for decreases in Q generation during multi-year droughts (Fowler et al., 2022). Here, we revealed that increases in E contributed (i) to decreases in summer low flows, in particular in catchments tending to arid, and (ii) to changes in the P - Q relationship during the multi-year drought that occurred in Germany between 1989 and 1993. With strong increases in E reported for many regions of the world over recent decades (Teuling et al., 2009; Ukkola & Prentice, 2013; Duethmann & Blöschl, 2018; Yang et al., 2023), these findings are relevant beyond our study region.

L396–397: (...) we underline the importance of monitoring changes in E for the prediction of potential decreases in Q during dry periods, particularly in arid regions.

L410–411: We illustrated the imprint of long-term increases in E on decreases in Q during dry conditions, which can be especially relevant for arid regions and prolonged droughts.

- 7. I am wondering why ET is increasing? The land cover change or the temperature increasing? Authors listed a lot of attributes of the catchments in table 1 but are limited used in the analysis.*

In Bruno & Duethmann (2024), we provided a first assessment of potential causes of past changes in E in small catchments in Germany, by showing that these changes were consistent with those in P and solar radiation. However, an in-depth investigation on the causes of past increases in E in the study region, including changes in land cover, would be noteworthy. Yet, we see this analysis as out of the scope of the current study. The catchment attributes in Table 1 are static attributes, which we used for a characterization of the study catchments. Additional, dynamic attributes would be needed to relate changes in E with changes in land cover for instance. To provide some background on possible causes of increases in E to the readers, we suggest adding this point to the Introduction as follows.

Increases in E followed changes in climate and land cover (Duethmann and Blöschl, 2018; Teuling et al., 2019; Yang et al., 2023; Bruno & Duethmann, 2024).

8. *Have you cited the paper talking about the similar thing? Tran et al. (2023), Frontiers in Water.*

Thank you for pointing to this piece of literature which we intend to add to the Introduction and Discussion.

Introduction: Furthermore, increases in E contributed to decreases in annual Q on the long-term (Teuling et al., 2009; Fischer et al., 2023) and during dry years, especially in mountain catchments (Tran et al., 2023).

Discussion: Our findings on the role of increases in E on decreases in summer low flows expand results at annual time scale (Fischer et al., 2023; Tran et al., 2023)

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